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ESSENTIALS

FOR THE

MICROSCOPICAL DETERMINATION

OF

ROCK-FORMING MINERALS AND ROCKS

ALBERT JOHANNSEN

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ESSENTIALS FOR THE MICROSCOPICAL DETERMINATION OF ROCK-FORMING MINERALS AND ROCKS

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ESSENTIALS

FOR THE

MICROSCOPICAL DETERMINATION

OF

ROCK-FORMING MINERALS AND ROCKS

IN THIN SECTIONS

BY ALBERT JOHANNSEN, PH.D.
PROFESSOR OF PETROLOGY
THE UNIVERSITY OF CHICAGO

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

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PREFACE

This laboratory manual contains practically all of the data originally published in the writer's *Determination of Rock-Forming Minerals*, and in addition gives modes of occurrence and many more points of separation between similar minerals. Only a few very rare species, such as johnstrupite, mosandrite, laavenite, etc., have been omitted, but by uniting the tables which contained minerals having birefringences greater or less than quartz, and refractive indices greater or less than Canada balsam, much repetition has been avoided, and the number of pages has been materially reduced. Orthorhombic minerals have been united with the other biaxial minerals, since sections which cut all of the crystallographic axes in this system show inclined extinction. The maximum extinction angles, of course, are given in the descriptions. The index of Canada balsam is shown on the diagrams at 1.537, the mean of that found in good sections.

The separation lines between the various plagioclase feldspars have been changed from those given in the former book to 5, 27½, 50, 72½, and 95 per cent anorthite. Albite and anorthite have been limited to a variation of only 5 per cent since these names are also applied to the pure end members, and compound names such as oligoclase-albite, labradorite-bytownite, etc., have been omitted.

The section on the determination of the feldspars has been but little reduced, but that on optical methods has been condensed as much as possible since this data is given elsewhere. *Manual*, throughout the text, refers to the author's *Manual of Petrographic Methods*, 2d edition, New York, 1918. The alphabetical list of minerals has been much extended, and is now placed at the back of the book in such a position that reference to it may be made without turning pages. Finally, a short section on the determination of rocks has been added, so that when minerals and their percentages have been determined, the rock name also may be known.

The writer has intentionally used words such as "sometimes," "often," and "occasionally" for "in some specimens," "in many localities," "here and there," and so on, believing that the use of adverbs of time for adverbs of place, especially in a book such as this, which is intended for laboratory use and which therefore should be as brief as possible, is justified by their use in this manner by many of the writers of the classics. Not only is this usage customary in English, but in foreign languages as well.

ALBERT JOHANNSEN

UNIVERSITY OF CHICAGO
April 18, 1922

KEY TO THE TABLES

				PAGE
Opaque				1
Isotropic				2
Anisotropic	Colorless	Uniaxial		4
		Biaxial		8
	Colored	Non-pleochroic	Uniaxial	14
			Biaxial	16
		Pleochroic	Uniaxial	20
			Biaxial	24

THE MINERAL IS OPAQUE

Yellow by incident light	Brass-yellow	Pyrite
	Bronze-yellow	Pyrrhotite
Black by incident light		Magnetite, Graphite, Ilmenite
Transparent on thin edges	Red	Hematite
	Brown	Chromite
	Greenish-brown	Picotite

Pyrite occurs in crystals and irregular grains as a primary accessory in igneous rocks, and abundantly in metamorphic rocks and sediments. It is non-magnetic, and insoluble in HCl. By incident light the color is lighter than that of p y r r h o t i t e .

Pyrrhotite occurs rarely in igneous rocks, abundantly with certain ore deposits. Pyrrhotite has a red-bronze to yellow-bronze color; p y r i t e is brass-yellow. Pyrrhotite is magnetic.

Magnetite occurs in the form of octahedrons, cubes, or irregular grains as a common accessory in all kinds of igneous rocks, most abundantly in those that are basic. It also occurs in metamorphic rocks and sediments. As a secondary mineral it is found in igneous rocks, in some cases in dustlike or dendritic forms. It is magnetic.

Graphite occurs in irregular flakes or scalelike aggregates, rarely in hexagonal plates, as a constituent of metamorphic rocks, schists, quartzites, marbles, rarely in pegmatites or other igneous rocks. May not be separable from magnetite when the latter occurs in irregular grains.

Ilmenite is an accessory mineral in igneous rocks, especially in diorites, gabbros, diabases, etc., also in metamorphic rocks. It occurs in hexagonal plates or grains, which in many cases are altered over the entire surface, or along lines intersecting at 60°, to a white decomposition product, usually titanite, called l e u c o x e n e . Titaniferous magnetite also may alter to leucoxene. Ilmenite rarely shows deep-brown thin edges.

In some cases magnetite, graphite, and ilmenite may not be separable under the microscope.

Hematite is found in rocks of all kinds, either as small hexagonal crystals, rare in igneous rocks, as pseudomorphs after magnetite, as rims around magnetite, as an alteration product from various ferromagnesian minerals, and as stains in cleavage cracks. It occurs in immense deposits among sediments. M a g n e t i t e is black by incident light, hematite is red. L i m o n i t e is usually yellow although it may be red, in which case it may be confused with hematite. In such cases it is customary to speak of the material as red-, brown-, or yellow iron oxide, and let it go at that.

Chromite is a mineral of peridotites and serpentines. It is black by incident light, sometimes brownish black on thin edges. In many cases it may not be possible to separate chromite from magnetite except by the reaction for chromium.

Picotite, the chrome spinel, occurs as an accessory in peridotites and other basic igneous rocks, in serpentines derived from peridotites, and rarely as crystals in basalts. It is greenish brown to yellowish brown on thin edges, and is isotropic.

THE MINERAL IS ISOTROPIC

Colorless	Refractive index is less than Canada balsam (1.537)	Occur as crystals	Fluorite	$n = 1.433$
			Sodalite	1.483
			Noselite	1.490
			Haüynite	1.503
			Leucite	1.508
		Fill cavities or are amorphous	Opal	1.443
			Glass	±1.490
		Cavity or interspace filling or attached crystals	Fluorite	1.433
			Analcite	1.488
	Refractive index is greater than Canada balsam	Form octahedrons, usually show quadratic sections	Spinel	1.716
			Periclase	1.736
		Usually in polygonal sections or rounded grains	Grossular	1.750
			Spessartite	1.811
Colored	Refractive index is less than Canada balsam	Occur as crystals	Fluorite	1.433
			Sodalite	1.483
			Noselite	1.490
			Haüynite	1.503
			Leucite	1.508
		Fills cavities or is amorphous	Glass	±1.490
	Refractive index is greater than Canada balsam	Form octahedrons, usually show quadratic sections	Spinel	1.718
			Periclase	1.736
			Hercynite	1.749
			Picotite	±1.7
			Gahnite	1.765
			Pleonaste	High
			Pyrrhite	High
			Beckelite	High
			Perofskite	2.38
		Rounded, quadratic, hexagonal, octahedral, etc., or in irregular grains. Usually with strong fractures	Grossularite	1.744
			Pyrope	1.744
			Almandite	1.810
			Spessartite	1.811
			Uwarowite	1.838
			Melanite	1.856

Fluorite, when colored, is readily separated from all other minerals of low index. The color, in many cases, is irregularly distributed. Cleavage (111) is perfect. The mineral rarely forms crystals, but generally occurs as cavity or interspace filling. It never shows anomalous double refraction. Sodalite and analcite, with which it may be confused when colorless, differ in cleavage, have anomalous double refraction in many cases, and occur in the alkalic rocks, while fluorite is especially confined to acid granites and pegmatites, frequently associated with topaz, tourmaline, and tin, where it was formed by pneumatolytic action.

Sodalite, a mineral of the nephelite- and other alkalic syenites, has a fair (110) cleavage while analcite has fair (100) cleavage. The two cannot be separated by optical means, but chemically the presence of chlorine indicates sodalite (*Manual*, p. 563). Optical anomalies are common in both.

Noselite, *haüynite*, and *leucite* always occur as crystals and are confined to igneous rocks, where they are primary minerals. Leucite occurs in six- or eight-sided to rounded grains, in many cases with characteristic radial or tangential inclusions in regular zones. Small leucites are generally isotropic, but larger grains are almost invariably polysynthetically twinned in a pattern resembling microcline, though of much lower birefringence (*Manual*, p. 510). Noselite and haüynite cannot be separated under the microscope by optical tests, but may be separated microchemically (*Manual*, p. 563).

Analcite is found filling veins and cavities in basalts, diabases, and other basic rocks, and as interspace filling in certain basaltic rocks, where it has been considered a primary mineral. It can be separated from sodalite only by microchemical means (*Manual*, p. 564). Anomalous double refraction is common.

Opal has no cleavage and may show anomalous double refraction. It occurs in cavities and veins in acid igneous rocks as a deposit from magmatic waters, and as nodules in limestones, shales, sandstones, silicified wood, etc.

Glass has no cleavage. It does not occur in the plutonic rocks except as inclusions in feldspars, etc., but is common in the acid extrusives. Its uniform distribution through the slide separates it from opal. Its lack of cleavage separates it from sodalite and analcite.

Spinel occurs as an accessory in peridotites and other basic igneous rocks, in serpentines derived from peridotites, in granular limestones, gneisses, etc. It is pale red, green, or blue, and has poor (111) cleavage.

Periclase is gray to yellow, and has good (100) cleavage. Both periclase and spinel occur in quadratic (111) crystals.

Hercynite is dark green, *picotite* is yellow-brown to greenish brown, *gahnite* is greenish black, *pleonaste* is green, *pyrrhite* is orange-yellow to red, *beckelite* is pale yellow, and *perofskite* is grayish white, brownish to red-brown, rarely greenish gray. Hercynite, gahnite, and pleonaste are separable only chemically, the others by color.

The garnets all show lack of cleavage, high relief, and isotropism.

Grossular is colorless to pale yellow. It may show anomalous double refraction. Zonal structure is common. Occurs in metamorphic calcareous rocks, as a contact mineral, or in crystalline schists.

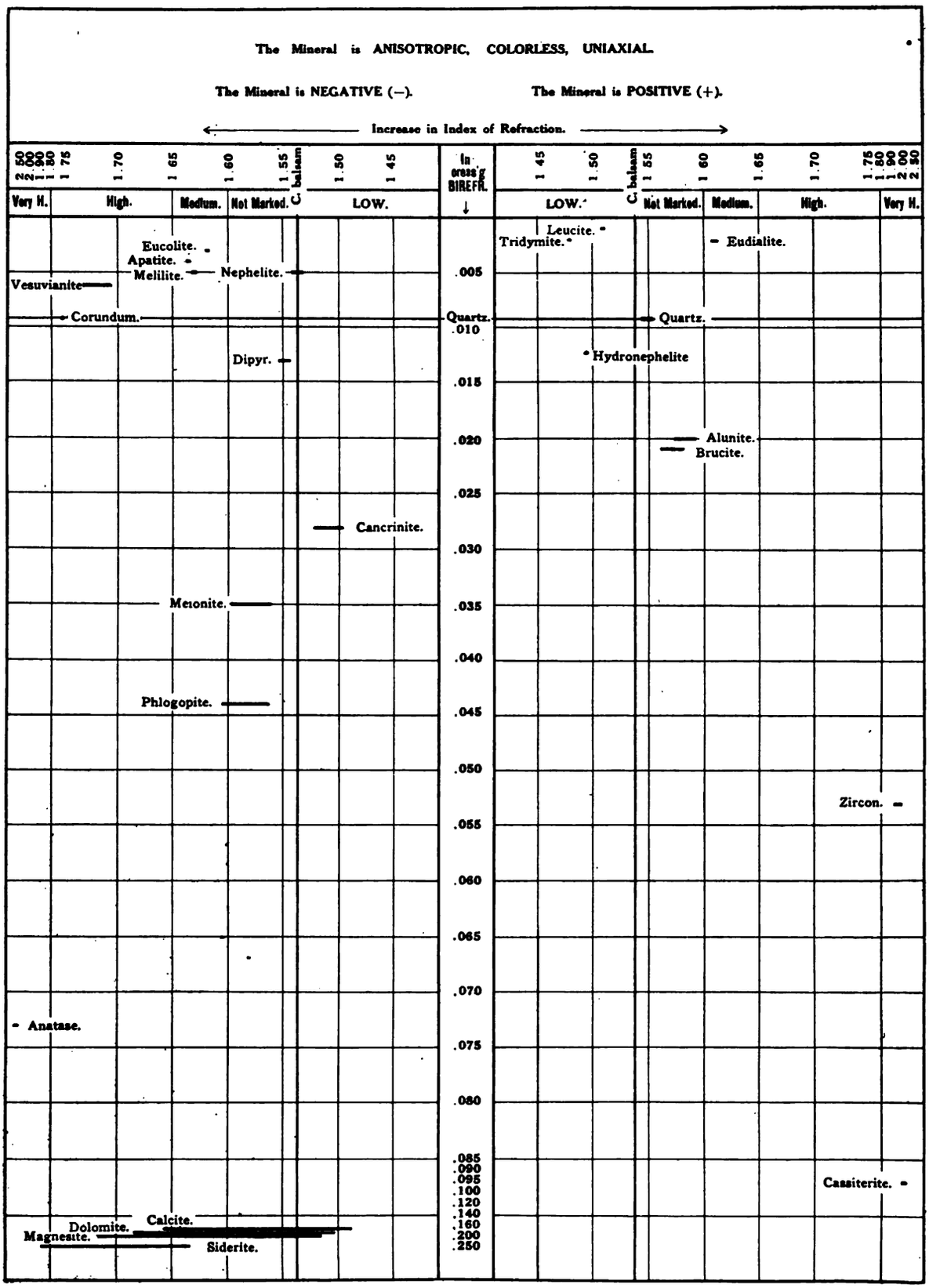
Spessartite is blood-red, yellowish red, or red-brown to colorless. Anomalous double refraction is common. It occurs in granites, a rhyolite (Colorado), and quartzites.

Pyrope is red to blood-red. Kelyphite rims are common. The mineral occurs only in peridotites, dunites, and their derivatives.

Almandite is red to red-brown, zonal structure is common, but anomalous double refraction does not occur. The mineral is found in igneous rocks which have been dynamo-metamorphosed, and in mica-schists and other metamorphic rocks.

Uwarowite is deep green and usually shows anomalous double refraction. It is confined to chromium-rich serpentines, granular limestones, and dolomites. Alterations are unknown.

Melanite occurs in various tones of dark brown, less commonly in green. Anomalies are hardly observable owing to the deep color. Zonal structure is common, but alterations are wanting. The mineral is found in various igneous rocks, especially phonolites, nephelinites, leucitites, tephrites, etc., also in contact metamorphosed rocks.


The Mineral is ANISOTROPIC, COLORLESS, UNIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
1.500 1.520 1.540 1.560 1.580 1.600 1.620 1.640 1.660 1.680 1.700 1.720 1.740 1.760 1.780 1.800 1.820 1.840 1.860 1.880 1.900 1.920 1.940 1.960 1.980 2.000 2.020 2.040 2.060 2.080 2.100 2.120 2.140 2.160 2.180 2.200 2.220 2.240 2.260 2.280 2.300 2.320 2.340 2.360 2.380 2.400 2.420 2.440 2.460 2.480 2.500 2.520 2.540 2.560 2.580 2.600 2.620 2.640 2.660 2.680 2.700 2.720 2.740 2.760 2.780 2.800 2.820 2.840 2.860 2.880 2.900 2.920 2.940 2.960 2.980 3.000
Very H.
High.
Medium.
Not Marked.
C. balsam
LOW.
Increasing BIREFR.
LOW.
C. balsam
Not Marked.
Medium.
High.
Very H.
Eucolite.
Apatite.
Melilite.
Nephelite.
Vesuvianite
Corundum.
Dipyr.
Cancrinite.
Meionite.
Phlogopite.
Anatase.
Dolomite.
Calcite.
Magnesite.
Siderite.
Leucite.
Tridymite.
Eudialite.
Quartz.
Hydronephelite
Alunite.
Brucite.
Zircon.
Cassiterite.
.005
.010
.015
.020
.025
.030
.035
.040
.045
.050
.055
.060
.065
.070
.075
.080
.085
.090
.095
.100
.120
.140
.160
.200
.250

The Mineral is Negative

Eucolite occurs in various nephelite-syenites. It has very weak (O>E) pleochroism or none. Cleavage (0001) is distinct. Anomalous 2E to 50°. Eudialyte is optically positive and has negative elongation. Topaz is biaxial. Apatite has poor cleavage, long crystals show parting, and elongation is negative. Melilite has characteristic abnormal Berlin blue interference color and basal cleavage.

Apatite has characteristic basal parting in long prisms. It is easily soluble in H_2SO_4 and the solution gives a yellow precipitate with ammonium molybdate (*Manual*, p. 565). Apatite is a very common accessory in the form of small prisms in most igneous rocks. In large crystals it occurs in pegmatites, some lamprophyres, etc. It is also found in crystalline schists, limestones, argillites, etc. Sillimanite has higher double refraction and positive elongation.

Melilite is a feldspathoid and does not occur in quartz-bearing rocks. It usually shows abnormal Berlin blue interference colors. The (001) and (110) cleavages are poor; only the basal cleavage is generally seen in thin sections, and this occurs as a single cleft along the middle of the lath-shaped section. Peg structure, due to inclusions growing inward from basal sections, is characteristic. It gelatinizes easily with HCl (*Manual*, p. 564). Vesuvianite and zoisite, both of which may give the abnormal blue interference color, are insoluble in acids. Vesuvianite has higher relief, and usually occurs as a contact mineral in limestone. Zoisite is biaxial and occurs as a secondary mineral.

Nephelite occurs in grains in soda-rich plutonic rocks, and in grains and quadratic sections in extrusives, but it is never found in the same rock with primary quartz. It has rather distinct (0001), (10$\bar{1}$0) cleavages. Anomalous biaxial character with small optic angle may occur. It gelatinizes easily with HCl (*Manual*, p. 564). Nephelite resembles quartz in appearance, but is negative. Cordierite is biaxial. Scapolites occur in metamorphic rocks, gneisses, crystalline schists, granular limestones, etc., but are rarely primary in igneous rocks.

The Mineral is Positive

Leucite is isometric at 433° C., but below that temperature is doubly refracting (*Manual*, p. 510). Characteristic radial or tangential inclusions, twinning, and crystal form separate it from all other minerals. It is found only in igneous rocks which are high in potash and low in silica, never in sediments or as a metamorphic mineral. It is fairly common among extrusives but is very rare among plutonites.

Tridymite is characterized by low refractive indices and by its occurrence in tabular, hexagonal, or rounded crystals, or in rosette-like aggregates, or in overlapping plates so small that edges appear like rectangular cleavage lines. Anomalous optic angle, 2E, may be as high as 70°. The mineral occurs in cavities in silicic extrusive rocks. It resembles no other minerals.

Eudialyte is optically positive and has negative elongation, while eucolite is negative and has positive elongation. Anomalous 2E may be as high as 50°. It is commonly associated with nephelite. See under eucolite.

Quartz usually shows no cleavage It may be separated from nephelite by the cleavage and negative character of the latter. Cordierite is biaxial and negative, with 2V from 40° to 84°, but quartz may show an anomalous optic angle, 2E, in some cases as high as 25°. When cordierite is treated with HF it gives characteristic prismatic crystals of magnesium fluosilicate. Scapolites are negative, show cleavage, and have higher double refraction.

Hydronephelite, a rare mineral in igneous rocks, has a poor (10$\bar{1}$0) cleavage and occurs in rodlike, leafy, or granular aggregates. It is separated from nephelite by its positive character and lower indices; from quartz by lower indices, from thomsonite by its lower birefringence. It is soluble in HCl with the formation of jelly.

Alunite occurs in veins in certain extrusive rocks and is formed by the action of SO_2 upon them. It has a good (0001) cleavage, which distinguishes it from quartz, as does also its higher birefringence.

The Mineral is Negative

Vesuvianite has poor (110), (100) cleavages. It usually occurs as a contact mineral derived from limestone, but has also been found in ancient ejected blocks among the dolomite masses of Vesuvius and Monte Somma. In some cases it shows abnormal Berlin blue interference colors, or biaxial character. It is insoluble in acids unless first fused. Zoisite has better cleavage and a different mode of occurrence.

Corundum occurs as a primary mineral in alumina-rich igneous rocks, both acid and basic, such as pegmatites, syenites, anorthosites, and dunites. It is rare as a contact mineral, but occurs in granular limestones and dolomites, gneisses, mica-schists, etc. The pleochroism, O = blue, red, E = sea-green, yellow, or greenish yellow, is seen only in deeply colored specimens. It has poor parting (10I1), (0001). The high relief separates it from similar minerals except vesuvianite from which it is separated by its hardness, higher double refraction, and by chemical means.

Dipyr (*mizzonite*), *wernerite* (common scapolite), and *meionite* are scapolites, and may be considered as isomorphous mixtures of the two molecules marialite (Ma) ($3Na_2O \cdot 3Al_2O_3 \cdot 18SiO_2 \cdot 2NaCl$) and meionite (Me) ($4CaO \cdot Al_2O_3 \cdot 6SiO_2$). $Ma_{100}Me_0$ to Ma_2Me_1 is called dipyr (mizzonite), Ma_2Me_1 to Ma_1Me_2 wernerite, and Ma_1Me_2 to Ma_0Me_{100} meionite. Where cleavage is not shown, scapolites resemble quartz, but their birefringence is greater and they are negative. The mode of occurrence and birefringence separate them from nephelite, as does also the cleavage, which appears right-angled in sections giving an interference figure. They occur in metamorphic rocks, gneisses, schists, in contact metamorphosed limestones, and as secondary minerals in calcium-rich basic rocks. Optical anomalies showing the opening of the interference cross are rare. They readily alter to mica, etc.

Cancrinite, a secondary mineral after nephelite, by some considered in part primary, resembles muscovite in its high interference colors, but its indices of refraction are less than Canada balsam. No other common mineral has such high colors and low indices except thomsonite and hydrargillite, but both of these are biaxial and positive. For chemical separation of cancrinite from nephelite and hydronephelite see elsewhere (*Manual*, pp. 564–65).

The Mineral is Positive

Brucite is a secondary mineral found in serpentines and magnesian limestones. It usually occurs in foliated or fibrous masses, sometimes spherical, or in plates. Anomalous biaxial character is not rare. Muscovite and talc are negative and have positive elongation. Hydromagnesite has lower birefringence and effervesces with HCl while brucite is soluble without effervescence. Gypsum is very similar in appearance, but its indices are lower than balsam, and it has inclined extinction.

Zircon has weak, seldom noticeable pleochroism. It occurs in small characteristic crystals which are shorter and stouter than those of apatite, and which have brilliant interference colors. In larger grains, the interference colors are pale and the mineral is brownish. Zircon is especially common in acidic and in sodic igneous rocks, but is also found in schists and gneisses, and as a residual mineral in the decomposition products of igneous rocks.

Cassiterite may be pleochroic in weak brownish tones. Cleavage (110) is poor, (100) distinct. Geniculated twins are common. It occurs as a pneumatolytic mineral in acid dikes and quartz veins, and as a rare primary mineral in some igneous rocks. Rutile has better cleavage and is not so brown, anatase is negative, brookite is biaxial, and perofskite is isotropic.

The Mineral is Negative

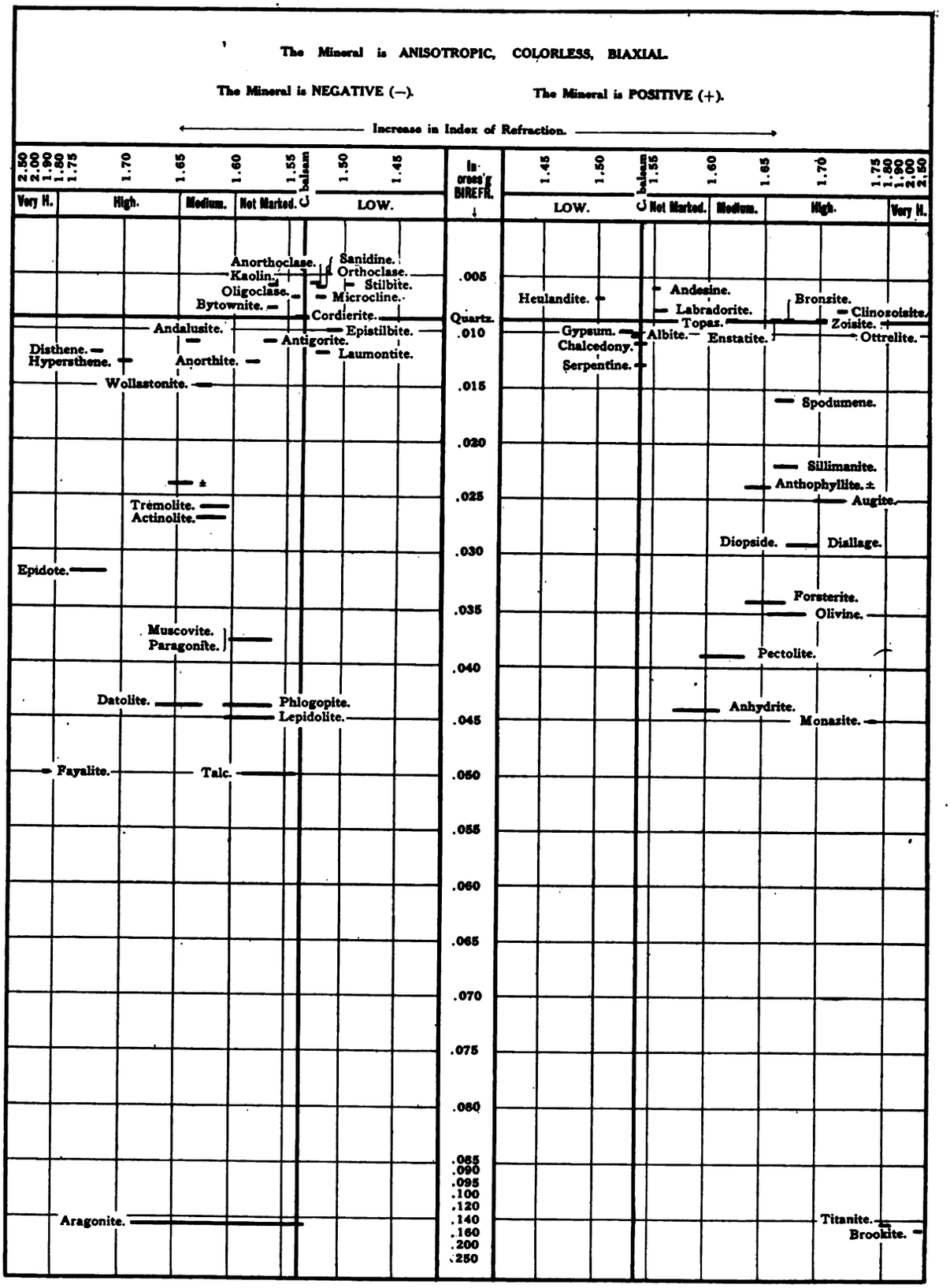
Meionite. See under dipyr, above.

Phlogopite is generally at least faintly colored with weak yellowish pleochroism. The "bird's-eye maple" appearance separates it from all minerals except other micas and talc. Its uniaxial interference figure separates it from all but talc and biotite. The former occurs only in basic rocks and is perfectly colorless or faintly green, the latter is usually strongly pleochroic. Bleached biotite may be colorless and impossible to separate from phlogopite.

Anatase occurs in pyramids and tablets, and is found in igneous rocks in some granite-pegmatites. It usually has pleochroism, O= deep blue or orange-yellow, E=light blue or light yellow, but it may be very weak so that the mineral appears colorless in thin sections. Colorless or yellow portions are usually normal, while blue portions show anomalous opening of the interference cross and do not fully extinguish. Perofskite differs in form, and the anomalous interference colors are lower than those in anatase.

Calcite, dolomite, and *magnesite* cannot be separated under the microscope, but may be by chemical means (*Manual,* p. 565). Aragonite is biaxial with $2V=18°$, and it differs in certain chemical reactions (*Manual,* p. 568). Brucite differs chemically (*Manual,* p. 567), and has much lower double refraction. Calcite is a common alteration mineral in all kinds of igneous rocks, and is said to be primary in some granites. Both calcite and dolomite occur as vein minerals, and in widespread and thick strata. Magnesite occurs as a secondary mineral derived from the alteration of magnesia-bearing minerals. It also occurs in talc-schists, serpentines, etc., often as veins.

Siderite has higher indices of refraction than the three preceding carbonates, and is usually somewhat yellowish or brownish. It is a common mineral of ore veins and of limestones. It is also found in gneisses, slates, shales, gray-wackes, etc.


The Mineral is ANISOTROPIC, COLORLESS, BIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
2.50 2.00 1.80 1.75 1.70 1.65 1.60 1.55 C. balsam 1.50 1.45
Very H. High. Medium. Not Marked. LOW.
Increas'g BIREFR.
1.45 1.50 C. balsam 1.55 1.60 1.65 1.70 1.75 1.80 1.900 2.00 2.50
LOW. Not Marked. Medium. High. Very H.
Anorthoclase.
Sanidine.
Kaolin.
Orthoclase.
Oligoclase.
Stilbite.
Bytownite.
Microcline.
Cordierite.
Andalusite.
Epistilbite.
Antigorite.
Disthene.
Hypersthene.
Anorthite.
Laumontite.
Wollastonite.
Tremolite.
Actinolite.
Epidote.
Muscovite.
Paragonite.
Datolite.
Phlogopite.
Lepidolite.
Fayalite.
Talc.
Aragonite.
.005
Quartz.
.010
.015
.020
.025
.030
.035
.040
.045
.050
.055
.060
.065
.070
.075
.080
.085
.090
.095
.100
.120
.140
.160
.200
.250
Heulandite.
Andesine.
Labradorite.
Bronzite.
Clinozoisite.
Topaz.
Zoisite.
Gypsum.
Albite.
Enstatite.
Ottrelite.
Chalcedony.
Serpentine.
Spodumene.
Sillimanite.
Anthophyllite. ±
Augite.
Diopside.
Diallage.
Forsterite.
Olivine.
Pectolite.
Anhydrite.
Monazite.
Titanite.
Brookite.

The Mineral is Negative

Kaolin usually appears as a flour-like, white, opaque alteration product of feldspar. It may be stained yellow or red by iron oxides. When crystallized it occurs in the form of leaves and scales with an extinction angle of 13°, and may be mistaken for sericite, although its birefringence is lower. Much so-called kaolin is colloidal aluminium silicate, and not kaolin. Muscovite (sericite) and hydrargillite have higher birefringences.

Anorthoclase (soda-microcline), *orthoclase*, *sanidine*, *oligoclase*, and *microcline* are feldspars. Special methods for their separation are given on pages 30–34. Anorthoclase, orthoclase, sanidine, and microcline have indices less than Canada balsam. Anorthoclase has 2V = 43°–53°, orthoclase 2V = 69°43′, 2E = 121°6′, sanidine 2V = small to 0°, microcline 2V = 83°. It may be impossible to separate anorthoclase and orthoclase under the microscope. Microcline is separated by the "grating" or plaid structure, due to the combination of polysynthetic albite and pericline twinning. Oligoclase usually has polysynthetic twinning with characteristic extinction angles, and refractive indices very near Canada balsam, in some sections greater in one direction and less in the other. All of these feldspars are separated from albite by the positive character of the latter, or by its extinction angle. Orthoclase and microcline may contain intergrown lamellae of albite (less commonly oligoclase), and are then called microperthite and microcline-microperthite. In anti-perthite, orthoclase forms lamellae in oligoclase or andesine.

Stilbite, one of the zeolites, occurs in rods, leaves, and sheaflike or radiating groups, in cavities in basalts, and less commonly in granites. The extinction angle $c:a$ is about 8°, and 2V is about 33°. It is decomposed by HCl without gelatinization.

Cordierite, orthorhombic, 2V from 40° to 84°, 2E from 63° to 150°, occurs in gneisses and various schists, rarely as a primary mineral in granites, andesites, etc. As a contact mineral it is found at the contact of acid igneous rocks with shales and slates. When treated with HF it gives characteristic prismatic crystals of magnesium fluosilicate. Pleochroic halos are occasionally seen in sections parallel to the c axis. Trillings and polysynthetic twins occur. Quartz is uniaxial and positive, albite is positive and has lower indices of refraction, nephelite is uniaxial.

The Mineral is Positive

Heulandite, a zeolite, occurs in leaves, plates, or rosettes, in basaltic rocks, rarely in gneiss. Its biaxial character (2E = 0°–55°), low indices and birefringence, and its habit separate it from other minerals.

Andesine and *labradorite* are plagioclase feldspars. They usually show polysynthetic twinning with characteristic angles. See pages 31–34.

Clinozoisite is an iron-poor or iron-free epidote with the composition of zoisite. It is colorless or reddish with weak or no pleochroism, extinction angle of 3°, and a large optic angle (2V = 80°–90°). It occurs in prisms or rods elongated on b, and in grains. Abnormal Berlin blue interference colors are common, as in zoisite, but this has parallel extinction and smaller optic angle (2V = 0°–60°). It may be impossible to separate the usual grains found in igneous rocks from zoisite. Pistacite has higher double refraction.

Topaz occurs as a pneumatolytic mineral in granite dikes, granites, rhyolites, and cassiterite-pegmatites, either in cavities or scattered through the rock. It is also found in the adjacent schists and gneisses. Cleavage is basal, but may not show in thin sections. Quartz has lower relief and is uniaxial. Andalusite is negative and usually has different mode of occurrence. Apatite is uniaxial and negative, while topaz has a large optic angle (2E = 71°–129°). Vesuvianite is usually slightly pleochroic and is uniaxial. Disthene is negative, 2V = 82°, and elongation is positive. Corundum is uniaxial and negative.

Enstatite has the usual pyroxene cleavage, parallel extinction (see note under hypersthene), 2E = 135°, and is non-pleochroic. Monoclinic pyroxenes have higher birefringence and inclined extinction in sections at right angles to the principal optic sections. In basal sections (which have sharp cleavage lines at angles of approximately 90° with each other) monoclinic pyroxenes show the emergence of an axis while orthorhombic pyroxenes show the emergence of a bisectrix. Bronzite is slightly pleochroic, hypersthene is pleochroic and negative.

Bronzite is essentially like enstatite but it is slightly pleochroic in green and pink tones. 2E = ±106°. Hypersthene has similar but stronger pleochroism and is negative. For separation from monoclinic pyroxenes, see under enstatite above.

The Mineral is Negative

Epistilbite, a zeolite with inclined extinction, $c:c = -9°$, occurs in basaltic rocks. It is imperfectly soluble in concentrated HCl without gelatinization. May not be possible to separate from stilbite, although the birefringence of the latter is lower.

Andalusite has characteristic though frequently faint pleochroism, a = rose, b = c = colorless to light green, resembling that seen in hypersthene. Hypersthene, however, has positive elongation, while andalusite has negative. Cleavage also differs, but the good (110) and less distinct (100) cleavage of andalusite may not be seen in thin sections, where the mineral often appears in irregular grains. In the schists the mineral usually occurs in characteristic irregular oval grains associated with grains of magnetite. In chiastolite the inclusions are found in regular arrangement, in the forms of rhombs, crosses, etc., in cross-sections and parallel to the long axes of prisms, and the material is often altered to a mica-like mineral. The higher relief separates andalusite from cordierite. Andalusite is found in a few granites, but is essentially a mineral of slates, schists, and gneisses. Chiastolite is a contact mineral in argillites near granitic intrusions.

Antigorite, the massive, lamellar serpentine, differs from common serpentine, which is fibrous, in being negative, and in its habit. Pennine, when optically negative, is separated by its optical character, when positive, by a chemical test for Al_2O_3. Pennine also has lower birefringence, usually abnormal interference colors, and pleochroism. Serpentines are always secondary and occur as an alteration product of olivine, less commonly of pyroxene or amphibole, and possibly also of other ferromagnesian minerals.

Disthene (cyanite) does not occur in igneous rocks, but chiefly in muscovite or paragonite schists, gneisses, eclogites, etc., often associated with garnets or corundum. The color is faint blue in thin sections, in some cases almost colorless. Cleavages, (100) perfect, (010) distinct, making an angle of 74°, are very characteristic, although they do not show in all sections. Orientation, a is nearly at right angles to (100), c is inclined 30° on (100) to the edge (100):(010). Sillimanite and andalusite are orthorhombic and have different cleavages, topaz has basal cleavage only, zoisite usually has abnormal interference colors and occurs in grains.

The Mineral is Positive

Zoisite, orthorhombic, is a mineral of the crystalline schist formations, produced by the dynamo-metamorphism of igneous rocks containing basic plagioclase. It also occurs in pegmatite dikes. Abnormal Berlin blue interference colors are common. Cleavage (010) good, (100) distinct. Clinozoisite has an extinction angle of 3° and an optic axial angle of $2V = 80°–90°$, while zoisite has an angle of 0°–60°. Melilite gelatinizes with acids, occurs only in quartz-free rocks, and has a characteristic habit. Vesuvianite has poorer cleavage and higher relief.

Gypsum is a mineral of the stratified rocks and occurs in connection with limestones and other rocks, but is rarely found in the crystalline schists. It resembles muscovite but the birefringence is lower, its extinction angle ($c:c = -52°$ to $-53°$) is higher (muscovite, $c:c = 0°–2°$), and it does not show the "bird's-eye maple" effect. Anhydrite is not so shredded and has higher double refraction as well as parallel extinction.

Albite, a plagioclase, usually shows polysynthetic twinning with characteristic extinction angles. When untwinned it resembles orthoclase, but is optically positive. Other plagioclases have higher refractive indices. See pages 31–32.

Ottrelite is a mineral almost exclusively confined to argillites altered by dynamo-metamorphism. It occurs in leaves and plates and usually shows hour-glass structure. Pleochroism may be rather weak or wanting, c = yellowish green, colorless, b = blue, a = olive-green. Cleavage (001) good. The low double refraction and high relief as well as its mode of occurrence separate it from all other minerals. Zoisite has parallel extinction and has different color and smaller optic angle. Clinozoisite has different cleavage ($001:100 = 64°37'$), and usually abnormal interference colors.

Chalcedony fills or lines cavities in rocks, or occurs in threadlike aggregates, concretionary masses, or spherulites. It is insoluble in HCl. $2V = 10°–40°$. Zeolites do not have threadlike habit and are soluble or gelatinize in acid. Pseudochalcedony is negative and has a small value for 2V.

The Mineral is Negative

Laumontite has an extinction angle of +20°, $c:c$, and occurs as small prisms in cavities in basalts and other basic extrusives, in pegmatites, syenites, etc. From epistilbite it is separated by its gelatinization in HCl and its extinction angle. Cancrinite has higher birefringence and is uniaxial, thomsonite is positive and has higher birefringence.

Hypersthene has characteristic pleochroism, c=greenish, a=reddish yellow, b=pink, fairly strong in iron-rich specimens but becoming fainter in bronzite. The extinction is parallel, but sections in which only one set of cleavage lines is brought out by grinding show inclined extinction, as do also, of course, all sections cutting the three axes. In basal sections (these show sharp cleavage lines at angles of approximately 90° with each other) monoclinic pyroxenes show the emergence of an axis while orthorhombic pyroxenes show the emergence of a bisectrix. The cleavage, $(110):(1\bar{1}0) = 91°40'$, is characteristic of all pyroxenes. Hypersthene occurs in all rocks from gabbroic rocks to granites. Bronzite is positive and has weaker pleochroism; andalusite, with similar pleochroism, has negative elongation and different cleavage.

Anorthite, the calcium plagioclase, shows polysynthetic twinning in most cases. See pages 30–34.

Wollastonite has (100) good and (001) distinct cleavages with an angle between them of 84.5°. Extinction angle $c:a = +32°12'$. It usually occurs in tablets or rods along the *b* axis, or reticulated or parallel in masses in granular limestones, at igneous contacts in lime rocks, but very rarely in igneous rocks themselves, then usually in calcareous inclusions. It gelatinizes with HCl. Pectolite and tremolite differ in not having the plane of the optic axes at right angles to the elongation, which is very characteristic of sections in the orthodiagonal zone of wollastonite. Pistacite has higher refraction and higher birefringence.

The Mineral is Positive

Serpentine is always secondary and occurs as an alteration product of olivine, less commonly of pyroxene or amphibole, and possibly of other ferromagnesian minerals. Antigorite is the massive, lamellar variety; here is included the fibrous variety. Antigorite is negative and massive. Pennine has lower double refraction, usually abnormal interference colors, and is pleochroic.

Spodumene has typical pyroxene cleavage, has extinction $c:c = -23°$ to $-26°$, and is generally non-pleochroic unless the sections are thick when a=amethyst, b=amethyst, c=colorless. In many cases it is altered to a mixture of albite and muscovite. It occurs in pegmatite veins, often of great size, and in granites and gneisses. Pleochroism, moderate birefringence, and occurrence separate it from other pyroxenes.

Sillimanite occurs as a contact mineral, and in long, slender, fine needles without terminal faces in the quartz of granites and gneisses. May also occur in prisms or aggregates of needles. Its (010) cleavage is perfect, and there are transverse fractures. Apatite, with similar cross-parting, has much lower double refraction and negative elongation. Andalusite is negative, has negative elongation, lower birefringence, and the relation of the axial plane to cleavage is different. Scapolites are negative, have negative elongation, and are uniaxial. Zoisite has weaker double refraction and different orientation.

Anthophyllite, an orthorhombic amphibole, usually fibrous, occurs in mica- and other schists as a contact mineral, and as an alteration product of olivine in serpentines, gabbros, peridotites, etc. It is usually non-pleochroic in thin sections, but may show c=yellowish, b=clove-brown, reddish, a=yellowish, greenish, colorless. Typical amphibole cleavage and parallel extinction separate it from other minerals. In basal sections showing sharp cleavage lines, a bisectrix appears in the center of the field; in monoclinic amphiboles this lies from a few degrees to twenty-two to the side.

Augite is usually green, brown, reddish, violet, or yellowish, but is rarely colorless. Pyroxene cleavage and high extinction angle ($c:c = -45°$ to $-55°$) characterizes it. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001). Augite is a common pyroxene in igneous rocks. It also occurs in metamorphosed sediments and metamorphosed igneous rocks.

The Mineral is Negative

Tremolite has typical amphibole cleavage, extinction $c:c = -16°$, and occurs as crystals, long or short, often bladed or fibrous, or compact, in metamorphosed magnesian limestones with little iron. Where iron is abundant, actinolite occurs, or where iron is the only carbonate, grünerite. Tremolite is hardly affected by HCl. Actinolite is pale green and slightly pleochroic, wollastonite gelatinizes with HCl and has the trace of the plane of the optic axes at right angles to the elongation.

Actinolite, with amphibole cleavage, extinction $c:c = -15°$, and similar in habit to tremolite, is rather a common mineral in certain schists and metamorphosed magnesian limestones containing much ferrous iron. It is green in color and has a faint pleochroism, sometimes hardly noticeable in thin sections, green to yellowish green.

Epidote (pistacite, green epidote) is a common contact or dynamo-metamorphic mineral in impure calcareous rocks, and a secondary mineral in the feldspars of many igneous rocks. It is often associated with clinozoisite. It has been described as primary in certain granites. It is sometimes very abundant with quartz in the rock called epidosite. Pistacite is the iron-rich epidote, clinozoisite the iron-poor or iron-free variety. The characteristic pistachio green color, brilliant interference colors, and high relief separate it from all other minerals. Pleochroism a = colorless to yellowish or greenish, b = yellowish to yellowish gray, c = green to light yellowish brown, sometimes rather weak. The plane of the optic axes lies at right angles to the elongation of the crystal.

Muscovite has a characteristic "bird's-eye maple" appearance, which separates it from all other minerals except the micas and talc. The optic axial angle ($2E = 60°–70°$) separates it from bleached biotite ($2E$ = small to $0°$). Paragonite can be separated only by chemical tests. Lepidolite usually has a smaller optic angle ($2E = 32°–84°$), but in some cases may not be distinguishable except by chemical tests. Talc has $2E = 6°–20°$, but in shreds it cannot be distinguished from muscovite except by chemical or physical tests, or by associated minerals. Primary muscovite never occurs with pyroxenes, talc usually does. The fine, shredded muscovite, secondary in potash feldspars, is called sericite. Do not call the secondary mica in plagioclase sericite unless you are certain that potash is present; the mica probably is secondary paragonite.

The Mineral is Positive

Diallage and *diopside* are monoclinic pyroxenes. The former has very perfect and abundant (100) cleavage in addition to the (110) cleavage of the latter. Both are pale green to colorless, and have extinction angles $c:c = -39°$. Diopside occurs in pyroxene-granites, diorites, lamprophyres, crystalline schists, and magnesia-rich marbles; diallage is common in gabbros and related rocks, and in peridotites and the serpentines derived from them. Pyroxene cleavage separates these minerals from all but other pyroxenes, from which the extinction angle separates them. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001).

Forsterite, the magnesia olivine, rarely occurs in igneous rocks, but is a mineral of dynamic and contact metamorphosed marbles, basic schists, and gneisses. It is colorless, and while it has a distinct cleavage (010), (001), this is usually seen only as heavy, irregular cracks. The mode of occurrence separates forsterite from olivine. The orientation of the interference figure (see under olivine) separates it from the pyroxenes.

Olivine, the intermediate magnesia-iron variety, is a common primary mineral in basic rocks, and an accessory in basic schists, gneisses, and marbles. It alters to actinolite, anthophyllite, iddingsite, magnetite, chromite, opal, quartz, serpentine, tremolite, and other minerals. Alteration to serpentine and magnetite are most common. It gelatinizes slowly in HCl. The interference figure lies parallel to (001), while in pyroxenes, in sections showing parallel extinction, it is parallel to (010). Fayalite has $2V = 50°$, higher birefringence, and is negative. Forsterite has a different mode of occurrence.

Pectolite usually occurs in tablets, rods along the b axis which are rarely terminated, or fibrous aggregates of acicular crystals, sometimes radiating. $2V = 60°$ and $c:c = -5°$. It occurs as a secondary mineral, like the zeolites, in cavities in basic igneous rocks, sometimes in metamorphosed rocks, and in nephelite-syenites. Wollastonite is negative, has ($\pm$) elongation, lower birefringence, and higher refractive indices, and $c:a = +32°$. Pyroxenes have different orientation of the interference figure.

The Mineral is Negative

Paragonite, the white soda mica analogous to muscovite, is common in certain schists (paragonite-schists) and probably as a secondary mineral from plagioclase (see under muscovite). It cannot be distinguished from muscovite optically.

Datolite rather rarely occurs in cavities in diabases and basalts, rarely in granites, diorites; also in gneiss. It has no distinct cleavage, and $c:a = 1°–4°$. It gelatinizes with HCl and gives reaction for boron. Green epidote has different color, cleavage, and lower birefringence.

Phlogopite is paler brown than biotite, reddish brown, or yellowish brown, sometimes greenish or colorless. 2V, as in biotite, is small to 0°. Biotite has stronger pleochroism, but when bleached may not be distinguishable from it. Phlogopite is essentially a mineral of marbles and crystalline dolomites, but does occur in the leucite rocks of Wyoming and in the mica-peridotites of southern Illinois. For separation from other minerals, see under muscovite.

Lepidolite, colorless to reddish, pink, or violet, in many cases resembles muscovite, from which its optic axial angle ($2E = 32°–84°$), when low, may separate it. The optic axial angle also separates it from bleached biotite (2V = small to 0°). In most cases it can be separated only from these micas by the reaction for Li. Lepidolite occurs in granite-pegmatite veins, greisen, and gneiss, often with tourmaline, cassiterite, etc.

Fayalite, the iron olivine, may be colorless or yellowish, greenish, reddish, with weak or no pleochroism in yellow and red tones. Olivine has $2V = 88°$ (fayalite, $2V = \pm 50°$), is optically positive, and has lower birefringence. Forsterite is positive, has $2V = 86°$, lower indices, and different mode of occurrence (contact mineral in metamorphic limestones).

Talc, orthorhombic, closely resembles muscovite in thin sections, and it may be necessary to use chemical means to separate them. The optic angle ($2E = 6°–20°$) is smaller than usual in muscovite, and the mode of occurrence is different, primary muscovite never occurring with pyroxene, while talc commonly does. It has the same "bird's-eye maple" appearance so common in mica.

Aragonite, under the microscope, resembles calcite, in refractive indices and double refraction, but it is biaxial ($2V = 18°$) and shows no cleavage. It occurs in gypsum deposits, occasionally in vesicules in basalt, and as the material of certain fossil shells and corals. For chemical separation from calcite see *Manual*, p. 568.

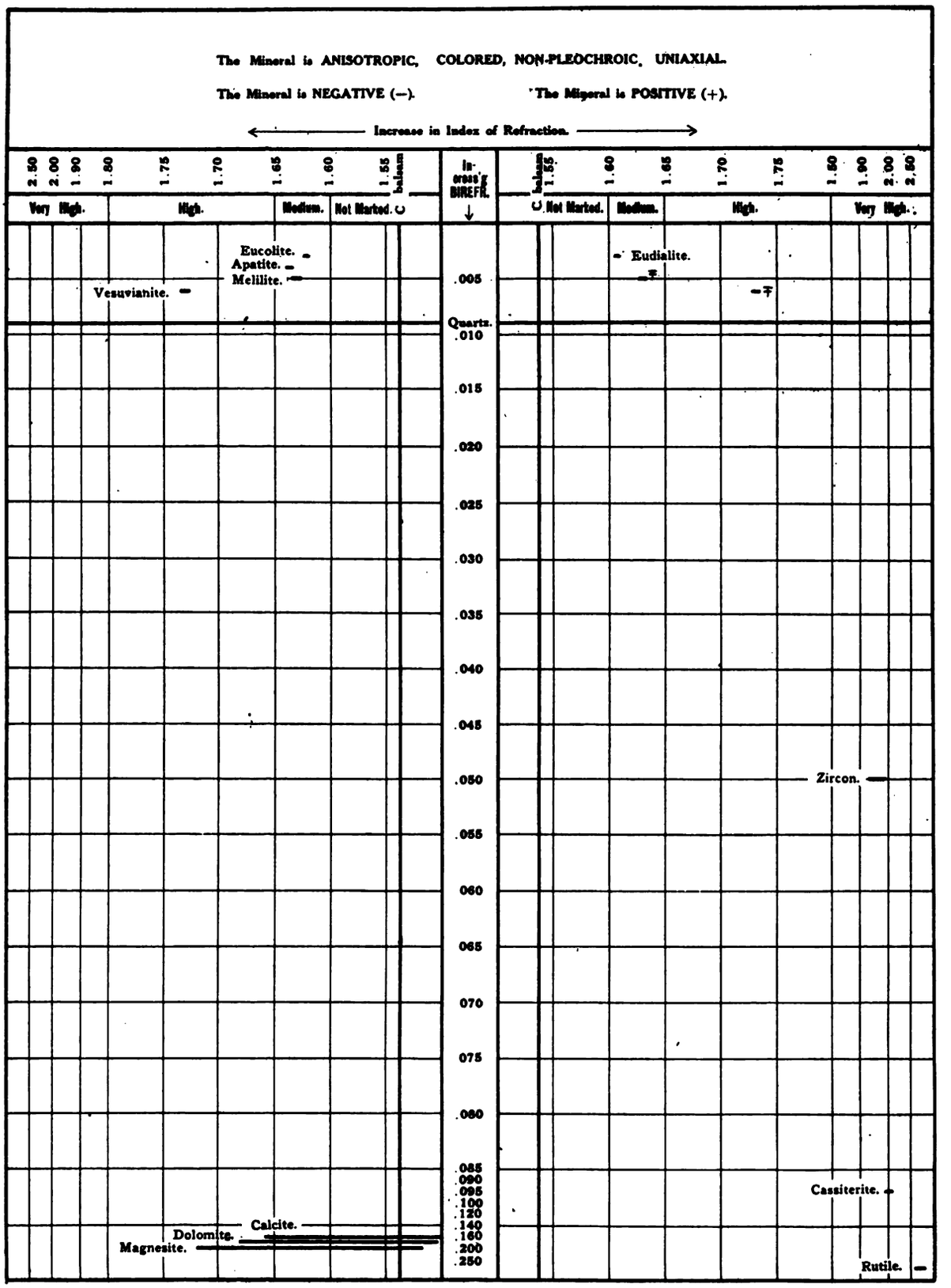
The Mineral is Positive

Anhydrite occurs in grains, sharp blades, seldom in threads in sedimentary beds associated with gypsum, in limestone, or with rock salt, and rarely in cavities in lava (Santorin). Gypsum has lower double refraction and $-53°$ extinction, disthene has lower birefringence and is negative.

Monazite occurs in granites, in gneissoid rocks, and in sediments, but most commonly in sands and gravels. The crystals are small, tabular parallel to (100) or elongated on the *b* axis, rounded grains, occasionally in larger masses. The yellow, non-pleochroic color, high birefringence, and high relief, separate it from most minerals. Titanite has higher birefringence, and the extinction angle is 39° (monazite, $c:c = 2°–6°$). Brookite has (±) elongation (monazite negative), and 2E is somewhat larger. Rutile has positive elongation, is usually of a deeper red or orange color, is uniaxial, has higher indices, and may show geniculated or heart-shaped twins.

Titanite is a very common accessory mineral in the acid plutonites, such as granites and syenites, abundant in nephelite-syenites, and less common in diorites. It is also abundant in gneisses and schists, and in some limestones. As a secondary mineral (*leucoxene*) it is derived from titaniferous magnetite, ilmenite, rutile, and other titanium-bearing minerals. The pleochroism is weak, $c > b > a$, in brown and yellow tones, $c:c = +39°$, and $2E = 45°–68°$. The strong dispersion produces colored isogyres. It occurs in the form of prisms, rhombs, and grains. Monazite has lower birefringence, smaller extinction angle, and weak dispersion. Brookite has parallel extinction, $2V = 0°$ to $-23°$. Rutile is uniaxial.

Brookite occurs in veins with various other minerals—albite, quartz, nephelite, garnets, rutile, chalcopyrite, galena, etc.—and in gold washings, always in the form of crystals of various habits, often tabular. The acute bisectrix is normal to (100) but the axial plane is parallel to (001) for red and yellow and parallel to (010) for green and blue. For red (670 $\mu\mu$) $2E = 58°0'$, yellow (589 $\mu\mu$) $2E = 38°10'$, yellowish green (555 $\mu\mu$) $2E = 0°$, green (535–525 $\mu\mu$) $2E = 21°40'–33°0'$ (*Manual*, pp. 444–45, and Figs. 619–23). Interference figure for white light is a combination of these, giving a peculiar form (*Manual*, Fig. 624). Cassiterite and rutile have different habit, and brookite has very different strength of double refraction in (100) and (010) sections.


The Mineral is ANISOTROPIC, COLORED, NON-PLEOCHROIC, UNIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
2.50 2.00 1.90 1.80 1.75 1.70 1.65 1.60 1.55 balsam
Very High. High. Medium. Not Marked. C
Increase BIREFR.
C. balsam 1.55 1.60 1.65 1.70 1.75 1.80 1.90 2.00 2.50
C. Not Marked. Medium. High. Very High.
Eucolite.
Apatite.
Melilite.
Vesuvianite.
Eudialite.
Quartz.
.005
.010
.015
.020
.025
.030
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.065
.070
.075
.080
.085
.090
.095
.100
.120
.140
.160
.200
.250
Zircon.
Cassiterite.
Calcite.
Dolomite.
Magnesite.
Rutile.

The Mineral is Negative

Eucolite occurs in various nephelite-syenites. It has very weak (O>E) pleochroism or none. Cleavage (0001) is distinct. Anomalous 2E to 50°. Eudialyte is optically positive, and has negative elongation. Topaz is biaxial. Apatite has poor cleavage, long crystals show parting, and elongation is negative. Melilite has characteristic abnormal Berlin blue interference color and basal cleavage.

Apatite has characteristic basal parting in long prisms. It is a very common accessory, in the form of small prisms, in most igneous rocks. In large crystals it occurs in pegmatites, some lamprophyres, etc. It is also found in the crystalline schists, limestones, argillites, etc. Sillimanite has higher double refraction and positive elongation.

Melilite is a feldspathoid and does not occur in quartz-bearing rocks. It usually shows abnormal Berlin blue interference colors. The (001) and (110) cleavages are poor; only the basal cleavage is generally seen in thin sections, and this occurs as a single cleft along the middle of the lath-shaped section. Peg structure, due to inclusions growing inward from basal sections, is characteristic. It gelatinizes with HCl (*Manual*, p. 564). Vesuvianite and zoisite, both of which may give the abnormal interference color, are insoluble in acids. Vesuvianite has higher relief, and usually occurs as a contact mineral in limestone. Zoisite is biaxial and occurs as a secondary mineral.

Vesuvianite has poor (110), (100) cleavages. It usually occurs as a contact mineral derived from limestone, but has also been found in ancient ejected blocks among the dolomite masses of Vesuvius. In some cases it shows abnormal blue interference colors, or biaxial character. Zoisite has better cleavage and a different mode of occurrence.

Calcite, *dolomite*, and *magnesite* cannot be separated under the microscope, but may be by chemical means (*Manual*, p. 565). Aragonite is biaxial with 2V=18°, and it differs in certain chemical reactions (*Manual*, p. 568). Brucite differs chemically (*Manual*, p. 567), and has much lower double refraction. Calcite is a common alteration mineral in all kinds of igneous rocks, and is said to be primary in some granites. Both calcite and dolomite occur as vein minerals, and in widespread and thick strata. Magnesite occurs as a secondary mineral derived from the alteration of magnesia-bearing minerals. It also occurs in talc-schists, serpentines, etc., often as veins.

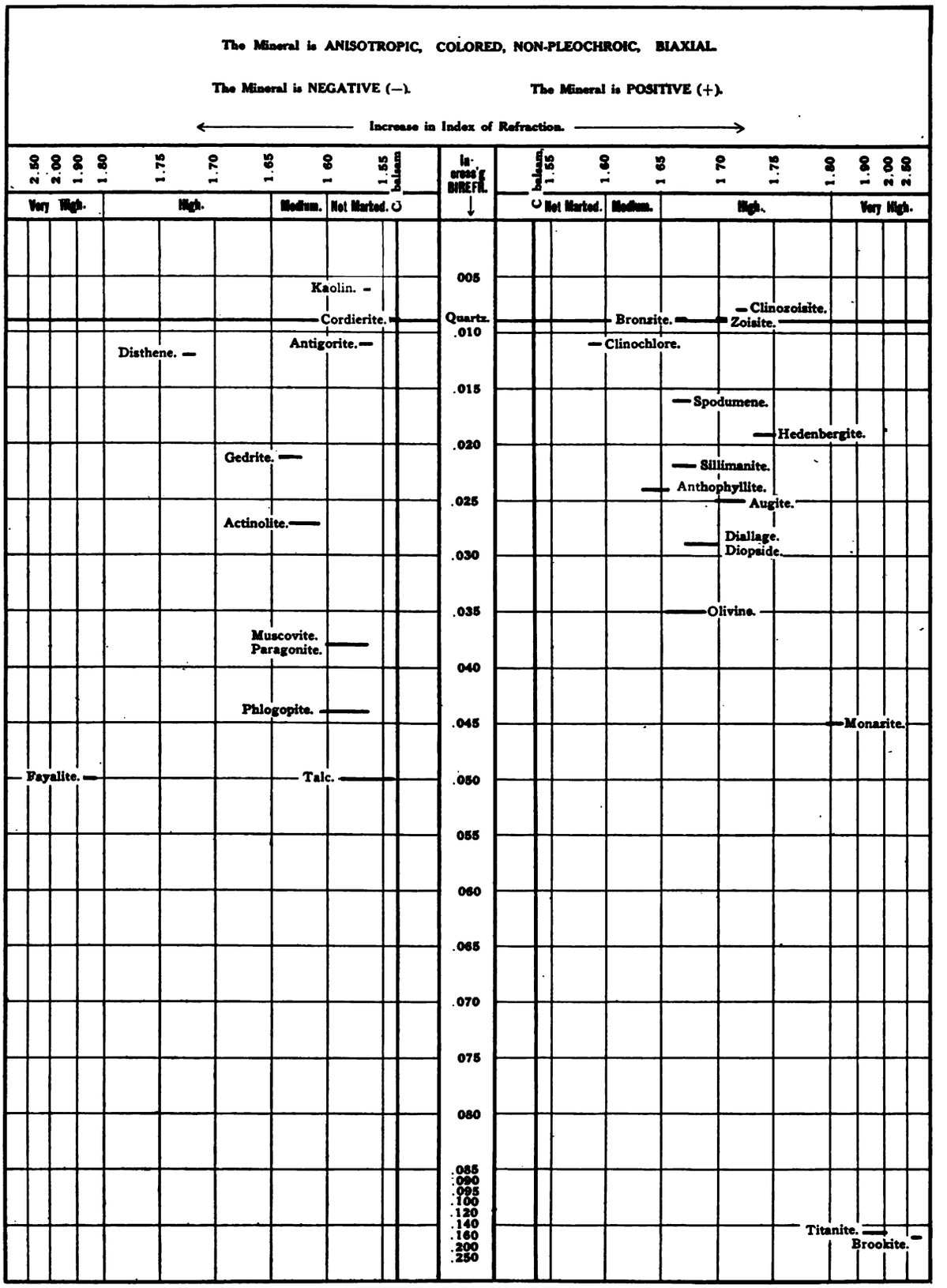
The Mineral is Positive

Eudialyte is optically positive and has negative elongation, while eucolite is negative and has positive elongation. Anomalous 2E may be as high as 50° (see eucolite). It is commonly associated with nephelite.

Zircon has weak, seldom noticeable pleochroism. It occurs in small characteristic crystals which are shorter and stouter than those of apatite and which have brilliant interference colors. In larger grains the interference colors are very high and pale, and the mineral is brownish. Zircon is especially common in acidic and sodic igneous rocks, but is also found in schists and gneisses, and as a residual mineral in decomposed igneous rocks.

Cassiterite may be pleochroic in weak brownish tones. Cleavage (110) is poor, (100) distinct. Geniculated twins are common. It occurs as a pneumatolytic mineral in acid dikes and quartz veins, and as a rare primary mineral in some igneous rocks. Rutile has better cleavage and is not so brown. Anatase is negative. Brookite is biaxial. Perofskite is isotropic.

Rutile occurs as an accessory mineral in granites, syenites, gneisses, and mica-schists, and as secondary microlites in argillites. It is also found in granular limestones, and has been found forming a dike with apatite. It occurs in grains, sometimes in geniculated twins, though usually in acicular crystals in quartz. It is also found regularly intergrown in phlogopite, biotite, and hematite, in so-called sagenite webs. Pleochroism seldom noticeable in thin sections, O=yellowish to brownish, E=brownish yellow to greenish yellow. Cassiterite has lower birefringence, poorer cleavage, anatase is negative and has much lower birefringence, brookite is biaxial and has different crystal form, and perofskite is isotropic.


The Mineral is ANISOTROPIC, COLORED, NON-PLEOCHROIC, BIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
2.50 2.00 1.90 1.80 1.75 1.70 1.65 1.60 1.55 balsam
Very High. High. Medium. Not Marked. C
Increas'g BIREFR.
C balsam. 1.55 1.60 1.65 1.70 1.75 1.80 1.90 2.00 2.50
C Not Marked. Medium. High. Very High.
Kaolin.
Cordierite.
Quartz.
Antigorite.
Disthene.
Gedrite.
Actinolite.
Muscovite.
Paragonite.
Phlogopite.
Fayalite.
Talc.
Bronzite.
Clinoclore.
Clinozoisite.
Zoisite.
Spodumene.
Hedenbergite.
Sillimanite.
Anthophyllite.
Augite.
Diallage.
Diopside.
Olivine.
Monazite.
Titanite.
Brookite.
005
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.090
.095
.100
.120
.140
.160
.200
.250

The Mineral is Negative

Kaolin usually appears as a flour-like, white, opaque alteration product of feldspar. It may be stained yellow or red by iron oxides. When crystallized it occurs in the form of leaves or scales with an extinction angle of 13°, and may be mistaken for sericite, although its birefringence is lower. Much so-called kaolin is colloidal aluminium silicate, and not kaolin. Muscovite (sericite) and hydrargillite have higher birefringences.

Cordierite, orthorhombic, 2V from 40°–84°, 2E from 63°–150°, occurs in gneisses and various schists, rarely as a primary mineral in granites, andesites, etc. As a metamorphic mineral it is found at the contact of acid igneous rocks with shales and slates. When treated with HF it gives characteristic prismatic crystals of magnesium fluosilicate. Pleochroic halos are occasionally seen in sections parallel to the *c* axis. Trillings and polysynthetic twins occur. Quartz is uniaxial and positive, albite is positive and has a lower index of refraction, nephelite is uniaxial and negative.

Antigorite, the massive, lamellar serpentine, differs from common serpentine, which is fibrous, in being negative, and in its habit. Pennine, when optically negative, is separated by its optical character, when positive, by a chemical test for Al_2O_3. Pennine also has lower birefringence, usually abnormal interference colors, and pleochroism. Serpentines are always secondary and occur as an alteration product of olivine, less commonly of pyroxene or amphibole, and possibly also of other ferromagnesian minerals.

Disthene (cyanite) does not occur in igneous rocks, but chiefly in muscovite or paragonite schists, gneisses, eclogites, etc., often associated with garnets or corundum. The color is faint blue in thin sections, in some cases almost colorless. Cleavages, (100) perfect, (010) distinct, making an angle of 74°, are very characteristic, although they do not show in all sections. Orientation, a is nearly at right angles to (100), c is inclined 30° on (100) to the edge (100):(010). Sillimanite and andalusite are orthorhombic and have different cleavages, topaz has basal cleavage only, zoisite usually has abnormal interference colors and occurs in grains.

The Mineral is Positive

Clinozoisite is an iron-poor or iron-free epidote, with the composition of zoisite. It is colorless to reddish with weak or no pleochroism, has extinction angle of 3°, and a large optic angle ($2V = 80°–90°$). It occurs in prisms or rods elongated on *b*, and in grains. Abnormal interference colors are common, as in zoisite, but zoisite has parallel extinction and smaller optic angle ($2V = 0°–60°$). It may be impossible to separate the usual grains found in igneous rocks from zoisite. Pistacite has higher double refraction.

Bronzite has the usual pyroxene cleavage, parallel extinction (see under hypersthene), and is slightly pleochroic in green and pink tones. $2E = \pm 106°$. Hypersthene has similar but stronger pleochroism and is negative. Monoclinic pyroxenes have higher birefringence and inclined extinction in sections at right angles to the principal optic sections. In basal sections which show sharp cleavage lines at approximately 90°, monoclinic pyroxenes show the emergence of an axis while orthorhombic pyroxenes show the emergence of a bisectrix. Enstatite is non-pleochroic.

Zoisite, orthorhombic, is a mineral of the crystalline schist formation, produced by the dynamo-metamorphism of igneous rocks containing basic plagioclase. It also occurs in pegmatite dikes. Abnormal blue interference colors are common. Cleavage (010) good, (100) distinct. Clinozoisite has an extinction angle of 3° and an optic angle of $2V = 80°–90°$, while zoisite has an angle of 0°–60°. Melilite gelatinizes with acids, occurs only in quartz-free rocks, and has a characteristic habit. Vesuvianite has poorer cleavage, and high relief.

Clinochlore, one of the chlorites, occurs in leaves, scales, plates, or leafy aggregates as a mineral of schists and serpentines, and in igneous rocks from the alteration of ferromagnesian silicates. $2E = 32°–90°$, $c:c = -2°$ to $-9°$, maximum birefringence = 0.011. Pennine is (±), $2E = 0° - 61°$, has parallel extinction, and maximum birefringence of 0.002.

Spodumene has typical pyroxene cleavage, extinction $c:c = -23°$ to $-26°$, is generally non-pleochroic unless the sections are thick, when a = amethyst, b = amethyst, c = colorless. In many cases it is altered to a mixture of albite and muscovite. It occurs in pegmatite veins, often of great size, and in granites and gneisses. Pleochroism, moderate birefringence, and mode of occurrence separate it from other pyroxenes.

The Mineral is Negative

Gedrite, an aluminium-bearing orthorhombic amphibole, occurs in metamorphic schists and gneisses, and as a contact mineral. It is usually pleochroic, c = yellowish, brownish, b = clove-brown, reddish, a = yellowish, greenish, colorless. Anthophyllite, the other orthorhombic amphibole, has 2V = 84°, while gedrite has 2V = 57°–79°.

Actinolite, with amphibole cleavage, extinction $c:c = -15°$, and similar in habit to tremolite, is rather a common mineral in certain schists and metamorphosed magnesian limestones containing much ferrous iron. It is green in color and has a faint green to yellowish green pleochroism, sometimes hardly noticeable in thin sections.

Muscovite has a characteristic "bird's-eye maple" appearance, which separates it from all other minerals except the micas and talc. The optic angle (2E = 60° – 70°) separates it from bleached biotite (2E = small to 0°). Paragonite can be separated only by chemical tests. Lepidolite usually has a smaller optic angle (2E = 32°–84°), but in some cases may not be distinguishable except by chemical means. Talc has 2E = 6°–20°, but in shreds it cannot be distinguished from muscovite except by chemical or physical tests, or by associated minerals. Primary muscovite never occurs with pyroxene, talc usually does. The fine shredded muscovite, secondary in potash feldspars is called sericite. Do not call the secondary mica in plagioclase sericite unless you are certain that potash is present; the mica probably is secondary paragonite.

Paragonite is the white soda mica analogous to muscovite. It is common in certain schists (paragonite-schists) and probably as a secondary mineral derived from plagioclase (see under muscovite). It cannot be distinguished from muscovite optically.

Phlogopite is paler brown than biotite, reddish brown, or yellowish brown, sometimes greenish or colorless. 2V, as in biotite, is small to 0°. Biotite has stronger pleochroism, but when bleached may not be distinguishable from it. Phlogopite is essentially a mineral of marbles and crystalline dolomites, but it does occur in the leucite rocks of Wyoming and in the mica-peridotites of southern Illinois. For separation from other minerals, see under muscovite.

The Mineral is Positive

Hedenbergite shows typical pyroxene cleavage. It occurs in some nephelite- and other basic syenites. 2V = 59°52′, $c:c = -44°$. Separated from other pyroxenes by its lower double refraction and by its extinction angle. Olivine has different orientation of the interference figure.

Sillimanite occurs as a contact mineral, and in long, slender, fine needles without terminal faces in the quartz of granites and gneisses. It may also occur in prisms or aggregates of needles. Its (010) cleavage is perfect, and there are transverse fractures. Apatite, with similar cross-parting, has much lower double refraction and negative elongation. Andalusite is negative, has negative elongation, lower birefringence, and the relation of the axial plane to the cleavage is different. Scapolites are negative, have negative elongation, and are uniaxial. Zoisite has weaker double refraction and different orientation.

Anthophyllite, an orthorhombic pyroxene, usually fibrous, occurs as a contact mineral in mica- and other schists, and as an alteration product of olivine in serpentines, gabbros, peridotites, etc. It is usually non-pleochroic in thin sections, but may show c = yellowish, b = clove-brown, reddish, a = yellowish, greenish, colorless. Typical amphibole cleavage and parallel extinction separate it from other minerals.

Augite is usually green, brown, reddish, violet, or yellowish, but rarely colorless. Pyroxene cleavage and high extinction angle ($c:c = -45°$ to $-55°$) characterizes it. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001). Augite is common in igneous and metamorphic rocks. It is of a brownish-purplish color when titaniferous, and, of that color, it is a common constituent of diabases and basalts.

Diallage and *diopside* are monoclinic pyroxenes. The former has very perfect and abundant (100) cleavage in addition to the (110) cleavage of the latter. Both are pale green to colorless, and have extinction angles of $c:c = -39°$. Diopside occurs in pyroxene-granites, diorites, lamprophyres, crystalline schists, and magnesia-rich marbles; diallage is common in gabbros and related rocks, and peridotites and the serpentines derived from them. Pyroxene cleavage separates these minerals from all but other pyroxenes, from which the extinction angle separates them. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001).

The Mineral is Negative

Fayalite, the iron olivine, may be colorless or yellowish, greenish, reddish, with weak or no pleochroism in yellow and red tones. Olivine has $2V=88°$ (fayalite, $2V=\pm 50°$), is optically positive, and has lower birefringence. Forsterite is positive, has $2V=86°$, lower indices, and different mode of occurrence (contact in metamorphic limestones).

Talc, orthorhombic, closely resembles muscovite in thin sections, and it may be necessary to use chemical means to separate them. The optic angle ($2E=6°$–$20°$) is smaller than usual in muscovite, and the mode of occurrence is different, primary muscovite never occurring with pyroxene, while talc commonly does. It has the same "bird's-eye maple" appearance so common in mica.

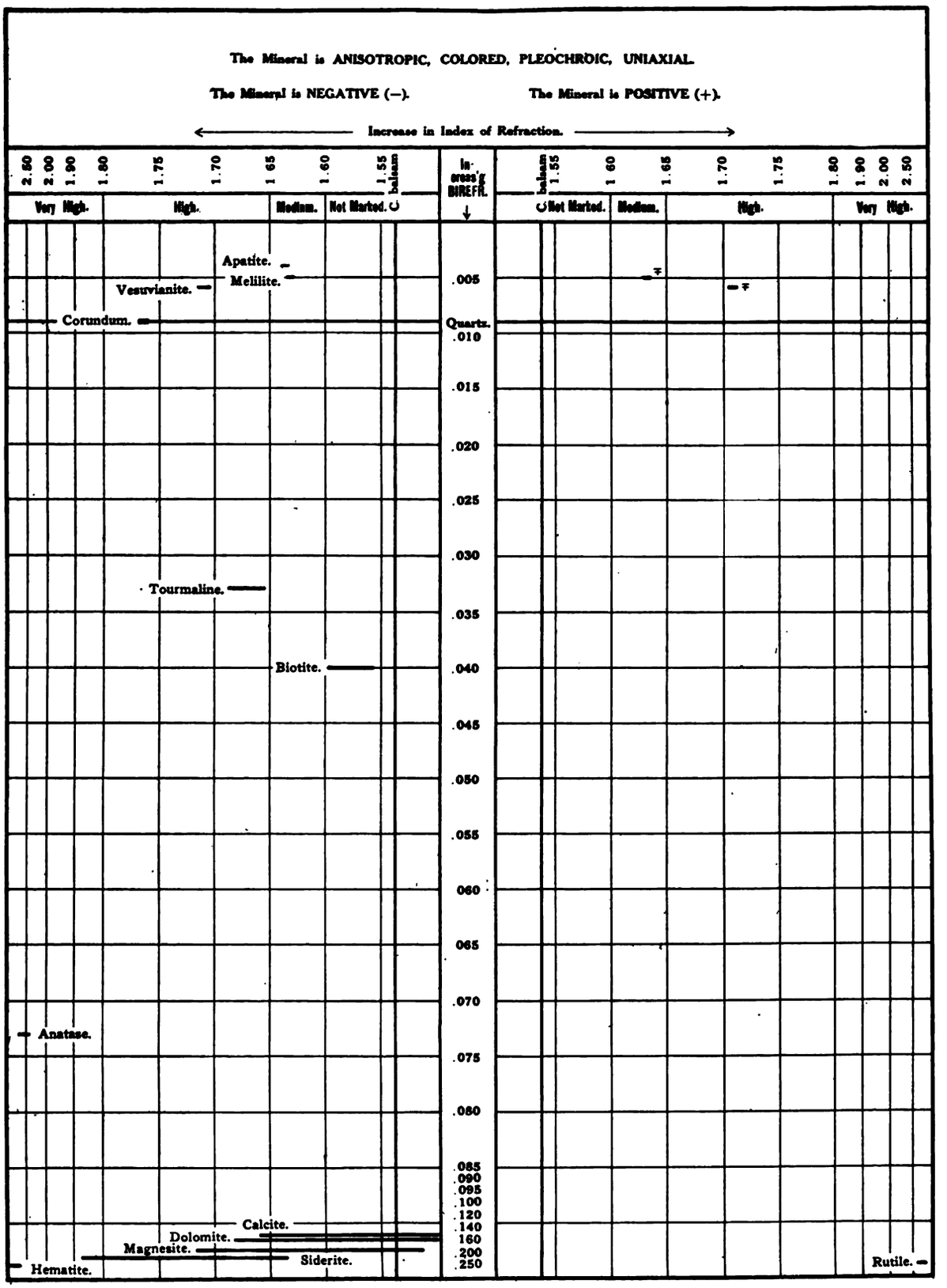
The Mineral is Positive

Olivine, the intermediate magnesia-iron variety, occurs as a common primary mineral in basic rocks, and as an accessory in basic schists, gneisses, and marbles. It alters to actinolite, anthophyllite, iddingsite, magnetite, chromite, opal, quartz, serpentine, tremolite, and other minerals. Alteration to serpentine and magnetite are most common. It gelatinizes slowly in HCl. The interference figure lies parallel to (001) while in pyroxenes, in sections showing parallel extinction, it is parallel to (010). Fayalite has $2V=50°$, higher birefringence, and is negative. Forsterite has a different mode of occurrence.

Monazite occurs in granites, in gneissoid rocks, in sediments, and most commonly in sands and gravels. The yellow, non-pleochrioc color, high birefringence and high relief, separate it from most minerals. Titanite has higher birefringence, the extinction angle is 39° (monazite, $c:c=2°$–$6°$), brookite has (±) elongation (monazite negative), 2E is somewhat larger. Rutile has positive elongation, is usually of a deeper red or orange color, is uniaxial, has higher indices, and may show geniculated or heart-shaped twins.

Titanite, in the form of prisms, rhombs, and grains, is a very common mineral in acid plutonites, such as granites and syenites, abundant in nephelite-syenites, and less common in diorites. It is also abundant in gneisses and schists, and in some limestones. As a secondary mineral (*leucoxene*) it is derived from titaniferous magnetite, ilmenite, rutile, and other titanium-bearing minerals. Pleochroism is weak $c>b>a$, in brown and yellow tones, $c:c=+39°$, and $2E=45°$–$68°$. Monazite has lower birefringence, smaller extinction angle, and weak dispersion. Brookite has parallel extinction, $2V=0°$ to $-23°$, and rutile is uniaxial.

Brookite occurs in veins with various other minerals such as albite, quartz, nephelite, garnets, rutile, chalcopyrite, galena, etc., and in gold washings, always in the form of crystals. The acute bisectrix is normal to (100) but the axial plane is parallel to (001) for red and yellow and parallel to (010) for green and blue. For red (670 $\mu\mu$) $2E=58°0'$, yellow (589 $\mu\mu$) $2E=38°10'$, yellowish green (555 $\mu\mu$) $2E=0°$, green (535 to 525 $\mu\mu$) $2E=21°40'$–$33°0'$ (*Manual*, pp. 444–45, Figs. 619–23). Interference figure for white light is a peculiar combination of all these (*Manual*, Fig. 624). Cassiterite and rutile have different habit, and brookite has very different strength of double refraction in (100) and (010) sections.


The Mineral is ANISOTROPIC, COLORED, PLEOCHROIC, UNIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
2.50 2.00 1.90 1.80 1.75 1.70 1.65 1.60 1.55 balsam
Increase BIREFR.
balsam 1.55 1.60 1.65 1.70 1.75 1.80 1.90 2.00 2.50
Very High. High. Medium. Not Marked. C
C Not Marked. Medium. High. Very High.
Apatite.
Melilite.
Vesuvianite.
Corundum.
Quartz.
Tourmaline.
Biotite.
Anatase.
Calcite.
Dolomite.
Magnesite.
Siderite.
Hematite.
Rutile.
.005
.010
.015
.020
.025
.030
.035
.040
.045
.050
.055
.060
.065
.070
.075
.080
.085
.090
.095
.100
.120
.140
160
.200
.250

The Mineral is Negative

Apatite has characteristic basal parting in long prisms. It is easily soluble in H_2SO_4 and the solution gives a yellow precipitate with ammonium molybdate (*Manual*, p. 565). Apatite, in the form of small prisms, is a very common accessory in most igneous rocks. In large crystals it occurs in pegmatites, some lamprophyres, etc. It is also found in crystalline schists, limestones, argillites, etc. Sillimanite has higher double refraction and positive elongation.

Melilite is a feldspathoid and does not occur in quartz-bearing rocks. It usually shows abnormal blue interference colors. The (001) and (110) cleavages are poor; only the basal cleavage is generally seen in thin sections, and this occurs as a single cleft along the middle of the lath-shaped section. Peg structure, due to inclusions growing inward from basal sections, is characteristic. It gelatinizes easily with HCl (*Manual*, p. 564). Vesuvianite and zoisite, both of which may give the abnormal blue interference color, are insoluble in acids. Vesuvianite has higher relief, and usually occurs as a contact mineral in limestone. Zoisite is biaxial and occurs as a secondary mineral.

Vesuvianite has poor (110), (100) cleavages. It usually occurs as a contact mineral derived from limestone, but has also been found in ancient ejected blocks among the dolomite masses of Vesuvius and Monte Somma. In some cases it shows abnormal Berlin blue interference colors, or biaxial character. It is insoluble in acids unless first fused. Zoisite has better cleavage and different mode of occurrence.

Corundum occurs as a primary mineral in alumina-rich igneous rocks, both acid and basic, such as pegmatites, syenites, anorthosites, and dunites. It is rare as a contact mineral, but occurs in granular limestones and dolomites, gneisses, mica-schists, etc. The pleochroism, O = blue, red, E = sea-green, yellow, or greenish yellow, is seen only in deeply colored specimens. It has a poor parting (10$\bar{1}$1), (0001). The high relief separates it from similar minerals except vesuvianite from which it is separated by its hardness, higher double refraction, and by chemical means.

The Mineral is Positive

Rutile occurs as an accessory mineral in granites, syenites, gneisses, and mica-schists, and as secondary microlites in argillites. It is also found in granular limestones, and has been found forming a dike with apatite. It occurs in grains, sometimes in geniculated twins, though usually in acicular crystals in quartz. It is also found regularly intergrown in phlogopite, biotite, and hematite, in so-called sagenite-webs. Pleochroism seldom noticeable in thin sections, O = yellowish to brownish, E = brownish yellow to greenish yellow. Cassiterite has lower birefringence, poorer cleavage; anatase is negative and has much lower birefringence; brookite is biaxial and has different crystal form, and perofskite is isotropic.

The Mineral is Negative

Tourmaline, a pneumatolytic mineral, occurs in granites and pegmatites, and rocks in contact with these, in schists, gneisses, talc-schists, and limestones and marbles. That found in marble is usually brown; in greisen and with tin ores usually blue-black; and in association with lepidolite red, yet these colors are not confined to the rocks mentioned, and two colors may occur together. Red and green transparent, and black opaque varieties also occur. It forms prisms, grains, and needles, the latter in many cases in radiating groups, so-called tourmaline suns, but the needles are not necessarily confined to one plane, but may radiate in all directions, giving in thin sections a central portion showing basal sections, characteristically three-, six-, nine-sided, etc., often zonal, surrounded by radiating crystals. The uniaxial character and the strong pleochroism, greatest in the direction at right angles to the vibration direction of the lower nicol, separate it from all other minerals, most of which are dark when the elongation is in the direction of vibration of the lower nicol.

Biotite is a common mineral of the acid and intermediate rocks, both plutonic and extrusive, and of some of the lamprophyres, and occurs as a metamorphic mineral in gneisses, schists, and various other rocks. In many cases it is intergrown with muscovite, either in parallel intergrowth or with muscovite forming the outer zone. Pleochroism, strong $c \gtrsim b > a$; c and b = deep brown to red-brown, deep green, a = light yellow to reddish, light greenish. It has a golden brown color in some nephelite-syenites. Basal sections are non-pleochroic and give nearly to quite uniaxial figures. "Bird's-eye maple" appearance is characteristic of all micas. Pleochroic halos about minute inclusions of zircon, etc., are common (*Manual*, p. 323). Tourmaline is darkest when its long direction is at right angles to the polarizer, lepidolite is non-pleochroic, zinnwaldite has less pleochroism and occurs in greisen and with tin deposits, but may require test for Li to distinguish, phlogopite is less pleochroic and generally occurs in crystalline limestones. Hornblende is biaxial, has inclined extinction, and does not show the "bird's-eye maple" effect.

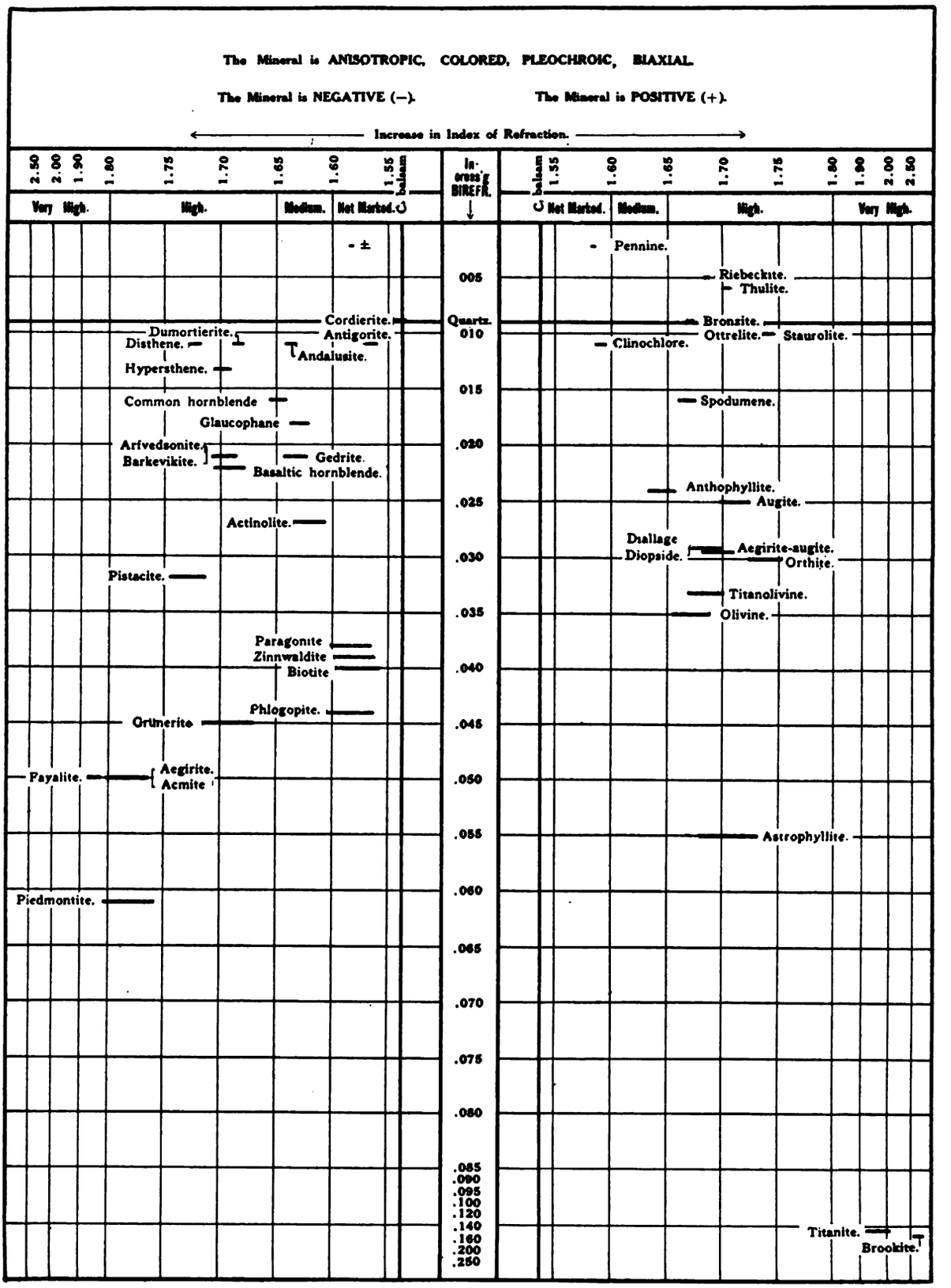
The Mineral is Negative

Anatase occurs in pyramids and tablets, and is found in some granite-pegmatites. It usually has pleochroism, O = deep blue or orange-yellow, E = light blue or light yellow, but it may be very weak, so that the mineral appears colorless in thin sections. Colorless or yellow portions are usually normal, while blue portions show anomalous opening of the interference cross and do not fully extinguish. Perofskite differs in form and the anomalous interference colors are lower.

Calcite, dolomite, and *magnesite* cannot be separated under the microscope, but may be by chemical means (*Manual,* p. 565). Aragonite is biaxial with $2V = 18°$, and differs in certain chemical reactions (*Manual,* p. 568). Brucite differs chemically (*Manual,* p. 567), and has much lower double refraction. Calcite is a common alteration mineral in all kinds of rocks, and is said to be primary in some granites. Both calcite and dolomite occur as vein minerals, and in widespread and thick strata. Magnesite occurs as a secondary mineral from magnesia-bearing varieties. It also occurs in talc-schists, serpentines, etc., often as veins.

Siderite has higher indices of refraction than the preceding three carbonates, and is usually somewhat yellowish or brownish. It is a common mineral of ore veins and of limestones. It is also found in gneisses, slates, shales, graywackes, etc.

Hematite is found in rocks of all kinds, either as small hexagonal crystals, rare in igneous rocks, as pseudomorphs after magnetite, as rims around magnetite, as an alteration product from various ferromagnesian minerals, and as stains in cleavage cracks. Also in immense deposits among sedimentaries. Pleochroism, O = brownish red, E = light yellowish red, not seen, of course, in basal sections nor in earthy varieties. Magnetite is black by incident light, hematite red; limonite is usually yellow, though it may be red, in which case it may be confused with hematite. In such cases it is customary to speak of the material as red-, brown-, or yellow iron oxide. Basal sections of some biotite may appear blood-red and closely resemble hematite, but the interference figure of hematite shows more rings in sections of the same thickness.


The Mineral is ANISOTROPIC, COLORED, PLEOCHROIC, BIAXIAL.
The Mineral is NEGATIVE (−).
The Mineral is POSITIVE (+).
Increase in Index of Refraction.
2.50 2.00 1.90 1.80 1.75 1.70 1.65 1.60 1.55 balsam
Very High. High. Medium. Not Marked. ☾
Increase BIREFR.
balsam 1.55 1.60 1.65 1.70 1.75 1.80 1.90 2.00 2.50
☾ Not Marked. Medium. High. Very High.
- ±
Cordierite.
Dumortierite.
Disthene.
Antigorite.
Andalusite.
Hypersthene.
Common hornblende
Glaucophane
Arfvedsonite.
Barkevikite.
Gedrite.
Basaltic hornblende.
Actinolite.
Pistacite.
Paragonite
Zinnwaldite
Biotite
Phlogopite.
Grünerite
Aegirite.
Acmite
Payalite.
Piedmontite.
Quartz.
.005
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Pennine.
Riebeckite.
Thulite.
Bronzite.
Ottrelite.
Staurolite.
Clinochlore.
Spodumene.
Anthophyllite.
Augite.
Diallage
Diopside.
Aegirite-augite.
Orthite.
Titanolivine.
Olivine.
Astrophyllite.
Titanite.
Brookite.

The Mineral is Negative

Cordierite, orthorhombic, 2V from 40° to 84°, 2E from 63° to 150°, occurs in gneisses and various schists, rarely as a primary mineral in granites, andesites, etc. As a metamorphic mineral it is found at the contact of acid igneous rocks with shales and slates. Pleochroic halos are occasionally seen in sections parallel to the *c* axis. Trillings and polysynthetic twins occur. Quartz is uniaxial and positive, albite is positive and has lower indices of refraction, and nephelite is uniaxial and negative.

Disthene (cyanite) does not occur in igneous rocks, but chiefly in muscovite- and paragonite schists, gneisses, eclogites, etc., often associated with garnets or corundum. The color is faint blue in thin sections, in some cases almost colorless. Cleavages, (100) perfect, (010) distinct, making an angle of 74°, are very characteristic, although they do not show in all sections. Orientation, a is nearly at right angles to (100), c is inclined 30° on (100) to the edge (100):(010). Sillimanite and andalusite are orthorhombic and have different cleavages, topaz has basal cleavage only, zoisite usually has abnormal interference colors and occurs in grains.

Dumortierite occurs in a few gneisses and similar rocks. It is characterized by its pleochroism, a = blue, b = yellowish, reddish violet, greenish, c = colorless; parallel extinction; good (100) cleavage; and small optic angle, 2V = 30°. Blue amphibole is monoclinic, andalusite and hypersthene have pink to green pleochroism, staurolite has higher relief, is positive, and is pleochroic in brown tones. Spodumene, when pleochroic, has amethystine colors and is positive.

Andalusite has characteristic though frequently faint pleochroism, a = rose, b = c = colorless to light green, resembling that seen in hypersthene. Hypersthene, however, has positive elongation and more marked cleavage. Andalusite frequently appears in irregular grains, or in more or less irregular oval forms associated with grains of magnetite in schists. In the variety chiastolite the inclusions are found in regular arrangement in the forms of rhombs, crosses, etc. in cross-sections and parallel to the long axes of prisms, and the material is altered to a mica-like mineral. The higher relief separates andalusite from cordierite. Andalusite is found in a few granites, but is essentially a mineral of slates, schists, and gneisses. As chiastolite it is a contact mineral in argillites near granitic contacts.

The Mineral is Positive

Pennine, one of the chlorites, occurs as an alteration product of biotite and other ferromagnesian minerals. It is usually nearly uniaxial, usually negative, sometimes positive, green in color with distinct pleochroism, b and a = green, c = yellowish, and with parallel extinction. Abnormal Berlin blue interference colors are common. Habit: leaves, scales, leafy aggregates, etc. Micas have higher birefringence and different pleochroism, serpentine has higher birefringence and lower indices and is seldom pleochroic. The separation from antigorite may be difficult and in some cases may be possible only chemically.

Riebeckite, an iron- and alkali-rich amphibole, occurs in igneous rocks rich in soda and iron, such as alkali-granites, and in metamorphosed igneous rocks and sediments. Extinction, c:a = 5°. Pleochroism, a = deep blue, b = lighter blue, c = yellowish green. Riebeckite is separated from other minerals by its amphibole cleavage, from other amphiboles except glaucophane, gastaldite, and arfvedsonite, by its blue color. Pleochroism in glaucophane is in violet tones, in arfvedsonite greenish blue and lavender. The latter also has a higher extinction angle, and both have higher birefringence than riebeckite, though this may be concealed by the deep color yet indicated by the number of rings in the interference figure (see top of page 39).

Thulite, the manganese zoisite, has a faint pleochroism, a = nearly colorless, b = rose, c = yellowish. It occurs in pegmatites and in crystalline schists. Zoisite is non-pleochroic, andalusite is optically negative, and green epidote has much higher birefringence.

Bronzite has the usual pyroxene cleavage, parallel extinction (see bottom, page 37), 2E = ±106°, and it is slightly pleochroic in pink and green tones. Hypersthene has similar but stronger pleochroism and is negative. Monoclinic pyroxenes have higher birefringences and inclined extinction in sections at right angles to the principal optic sections. In basal sections (which have sharp cleavage lines at angles of approximately 90° with each other) monoclinic pyroxenes show the emergence of an axis while orthorhombic pyroxenes show the emergence of a bisectrix. Enstatite is non-pleochroic.

The Mineral is Negative

Antigorite, the massive, lamellar serpentine, differs from common serpentine, which is fibrous, in being negative, and in its habit. Pennine, when optically negative, is separated by its optical character, when positive, by a chemical test for Al_2O_3. Pennine also has lower birefringence, usually abnormal interference colors, and pleochroism. Serpentine is always secondary and occurs as an alteration product of olivine, less commonly of pyroxene or amphibole, and possibly also of other ferromagnesian minerals.

Hypersthene has characteristic pleochroism, c = greenish, a = reddish yellow, b = pink, fairly strong in iron-rich specimens but fainter in bronzite. The extinction is parallel, but sections in which only one set of cleavage lines is brought out by grinding show inclined extinction, as do also, of course, all sections cutting the three axes. In basal sections (these show sharp cleavage lines at approximately right angles to each other) monoclinic pyroxenes show the emergence of an axis while orthorhombic pyroxenes show the emergence of a bisectrix. The cleavage, $(110):(1\bar{1}0) = 91°40'$, is characteristic of all pyroxenes. Hypersthene occurs in all rocks from the gabbro family to granites. Bronzite is positive and has weaker pleochroism; andalusite, with similar pleochroism, has negative elongation and different cleavage.

Common hornblende, a widespread monoclinic mineral in acid and intermediate igneous rocks, is strongly pleochroic in green, rarely brown, tones. Pargasite is the name applied to the green varieties, common hornblende to the brown and black varieties, although the name hornblende is applied to all. Hornblende occurs also in limestones and is widespread among the schists and other metamorphic rocks. Arfvedsonite has negative elongation; other amphiboles have different extinction angles. Amphibole cleavage separates hornblende from all other minerals.

Glaucophane, with $(110):(1\bar{1}0) = 55°16'$, resembles amphibole in habit. It occurs in grains, prisms, and fibers. The pleochroism is characteristic, a = nearly colorless to yellowish green, b = reddish to bluish violet, c = blue, $c:c = -4°$ to $-6°$, $2V = 45°$, $2E = 85.5°$, but the mineral sometimes appears nearly uniaxial. Glaucophane is a metamorphic mineral of mica-schists, amphibolites, and gneisses, especially those derived from basic rocks which formerly contained much soda. Garnets, mica, omphacite, epidote, zoisite, etc., are frequent associates.

The Mineral is Positive

Ottrelite is a mineral almost exclusively confined to argillites altered by dynamo-metamorphism. It occurs in leaves and plates, and usually shows hour-glass structure. Pleochroism may be rather weak or wanting, c = yellowish green, colorless, b = blue, a = olive-green. Cleavage (001) good. The low double refraction and high relief, as well as the mode of occurrence, separate it from all other minerals. Zoisite has parallel extinction, different color, and smaller optic angle. Clinozoisite has different cleavage ($001:100 = 64°37'$), and usually abnormal interference colors.

Staurolite occurs in crystalline schists as a contact or dynamo-metamorphic mineral. Inclusions symmetrically arranged or in subparallel bands are common. The yellow, red, or brown color, the pleochroism, c = red-brown, a and b = yellow, the parallel extinction, the large optic angle, $2V = 89°$, giving a straight bar in sections at right angles to an optic axis, separate it from other minerals. Andalusite is negative and has different pleochroism, gedrite has smaller optic axial angle ($2V = 57°$–$79°$) and amphibole cleavage, anthophyllite has amphibole cleavage and is rarely pleochroic in thin sections, vesuvianite has a pale yellow color, is negative, and has lower birefringence.

Clinochlore, one of the chlorites, occurs in leaves, scales, plates, or leafy aggregates as a mineral of schists and serpentines, and as a secondary mineral in igneous rocks from the alteration of ferromagnesian silicates. $2E = 32°$–$90°$, $c:c = -2°$ to $-9°$, maximum birefringence = 0.011. Pennine is (±), $2E = 0°$–$61°$, has parallel extinction, and the maximum birefringence is 0.002.

Spodumene has typical pyroxene cleavage, extinction $c:c = -23°$ to $-26°$, is generally non-pleochroic unless the sections are thick, when a = amethyst, b = amethyst, c = colorless. In many cases it is altered to a mixture of albite and muscovite. It occurs in pegmatite veins, often in very large crystals, and in granites and gneisses. Pleochroism, moderate birefringence, and mode of occurrence separate it from other pyroxenes.

Anthophyllite, an orthorhombic pyroxene, usually fibrous, occurs in mica- and other schists as a contact mineral, and as an alteration product of olivine in serpentines, gabbros, peridotites, etc. It is usually non-pleochroic in thin sections, but may show c = yellowish, b = clove-brown, reddish, a = yellowish, greenish, colorless. Typical amphibole cleavage and parallel extinction separate it from other minerals.

The Mineral is Negative

Arfvedsonite, rather a rare mineral, occurs in soda-bearing igneous rocks, as nephelite-syenites, phonolites, tinguaites, pantellerites, and alkali-pegmatites. It has amphibole cleavage and is characterized by strong pleochroism, a = pale greenish yellow, b = lavender, c = deep greenish blue. Absorption c > b > a. 2V is large, and the mineral is probably optically positive, *c*:c on (010) = 14°. Glaucophane has positive elongation and *c*:c = −4° to −6°. Riebeckite has *c*:c = −85° (*c*:a = 5°), aegirite has different color, barkevikite has 2V = about 54°, *c*:c = 14°, and the color is brown.

Barkevikite, a rare brown amphibole, has *c*:c = 14°, and is strongly pleochroic in brown tones. A sharp separation between barkevikite and basaltic hornblende is not possible. Other amphiboles differ as mentioned under arfvedsonite.

Gedrite, an aluminium-bearing orthorhombic amphibole, occurs in metamorphic schists and gneisses, and as a contact mineral. It is usually pleochroic, c = yellowish, brownish, b = clove-brown, reddish, a = yellowish, greenish, colorless. Anthophyllite, the other orthorhombic amphibole, has 2V = 84°, while gedrite has 2V = 57°–79°.

Basaltic hornblende is common in basic extrusives. It frequently shows absorption rims. It is pleochroic in strong brown and yellow tones, with c > b > a, also in green and brown tones with a = green, b and c = brown. Common hornblende has *c*:c = −12° to −20°, sometimes positive character, lower double refraction, and sometimes lower 2V. Biotite generally has the "bird's-eye maple" effect. See under arfvedsonite.

Actinolite, with amphibole cleavage, extinction *c*:c = −15°, and a habit similar to tremolite, is rather a common mineral in certain schists and metamorphic magnesian limestones containing much ferrous iron. It is green in color and has a faint green to yellowish green pleochroism, sometimes hardly noticeable in thin sections.

The Mineral is Positive

Augite is usually green, brown, reddish, violet, or yellowish, but rarely colorless. Pyroxene cleavage and high extinction angle (*c*:c = −45° to −55°) characterize it. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001). Augite is a common pyroxene in igneous rocks, and it also occurs in metamorphosed sediments and igneous rocks. It is of a brownish-purplish color when titaniferous, and, with that color, it is a common constituent of diabases and basalts.

Diallage and *diopside* are monoclinic pyroxenes. The former has very perfect and abundant (100) cleavage in addition to the (110) cleavage of the latter. Both are pale green to colorless, and have extinction angles of *c*:c = −39°. Diopside occurs in pyroxene-granites, diorites, lamprophyres, crystalline schists, and magnesia-rich marbles; diallage is common in gabbros and related rocks, and in peridotites and the serpentines derived from them. Pyroxene cleavage separates these two minerals from all but other pyroxenes, from which the extinction angle separates them. In sections showing parallel extinction, the plane of the optic axes is parallel to (010), in olivine it is parallel to (001).

Aegirite-augite, a pyroxene of the igneous rocks rich in sodium, especially of nephelite-syenites, phonolites, leucitophyres, etc., also of some alkali-granites and -syenites, shows the extinction angle of augite but the peculiar green color of aegirite. Pleochroism is the same as in aegirite, a = grass-green, b = light green, c = yellowish to brownish. Optically it is probably positive. Aegirite is negative and has an extinction angle, *c*:a = about 5°, augite has different color and slight pleochroism.

Orthite (allanite), the cerium epidote, occurs in various granitic rocks, in the form of grains, prisms, and rods along *b* or *c*, with high (0.032) birefringence in fresh material but sinking to zero when the mineral is altered to a megascopically gumlike substance. Cleavage (001) is distinct. Zones not uncommon. Pleochroism, strong, in fresh material, a = greenish brown, b = reddish brown, c = brownish yellow. Brown hornblende has smaller extinction angle, and distinct cleavage, rutile and cassiterite are uniaxial and have higher birefringences and indices of refraction.

Titanolivine resembles olivine in having no cleavage, but it is pleochroic with a = red, b = c = light yellow. 2V = 62°–63°. The transition between olivine and titanolivine is usually gradual.

The Mineral is Negative

Epidote (pistacite, green epidote) is a common contact or dynamo-metamorphic mineral in impure calcareous rocks, and a secondary mineral in the feldspars of many igneous rocks. It is often associated with clinozoisite. It has been described as primary in certain granites. Pistacite is the iron-rich epidote, clinozoisite the iron-poor or iron-free variety. The characteristic pistachio green color, brilliant interference colors, and high relief separate it from all other minerals. Pleochroism, a = colorless to yellowish or greenish, b = yellowish to yellowish gray, c = green to light yellowish brown, sometimes rather weak. The plane of the optic axes lies at right angles to the elongation of the crystal.

Paragonite is common in certain schists and probably also occurs as a secondary mineral from plagioclase (see under muscovite). It cannot be distinguished optically from muscovite.

Zinnwaldite is the lithia-iron mica between lepidolite and biotite. It is found in greisens and rocks associated with tin ores. It has weaker pleochroism than biotite, $c > b > a$, with c and a = dark brown, brownish gray, b = yellowish brown or reddish, nearly colorless. Orientation as in biotite: $b = b$, $c:a = 0°$ to $+7°$, $2E = 10°$–$60°$. Lepidolite has a different position of the plane of the optic axes ($b = c$, $c:a = 0°$ to $+2°$, rarely $b = b$, $c:c = 0°$ to $+2°$). It may be impossible to separate this mineral from biotite except by the reaction for lithium.

Biotite is a common mineral of the acid and intermediate igneous rocks. It also occurs as a metamorphic mineral in gneisses, schists, and various other rocks. In many cases it is intergrown with muscovite, either in parallel position or with muscovite forming the outer zone. Pleochroism, strong $c \gtrsim b > a$; c and b = deep brown to red-brown, deep green, a = light yellow to reddish, light greenish. Has a golden brown color in some nephelite-syenites. Basal sections are non-pleochroic and give nearly or quite uniaxial figures. "Bird's-eye maple" appearance is characteristic of all micas. Pleochroic halos about minute inclusions of zircon, etc., are common (*Manual*, p. 323). Tourmaline is darkest when its long direction is at right angles to the polarizer; lepidolite is non-pleochroic; zinnwaldite has less pleochroism, and occurs in greisens and with tin deposits, but may require test for Li to distinguish. Phlogopite is less pleochroic and generally occurs in crystalline limestones. Hornblende is biaxial, has inclined extinction, and does not show the "bird's-eye maple" appearance.

The Mineral is Positive

Olivine, the intermediate magnesia-iron variety, is a common primary mineral in basic rocks. It also occurs as an accessory in basic schists, gneisses, and marbles. It alters to actinolite, anthophyllite, iddingsite, magnetite, chromite, opal, quartz, serpentine, tremolite, and other minerals. Alteration to serpentine and magnetite are most common. It gelatinizes slowly with HCl. The plane of the optic axes is parallel to (001) while in pyroxenes, in sections showing parallel extinction, it is parallel to (010). Fayalite has $2V = 50°$, higher birefringence, and is negative. Forsterite has a different mode of occurrence.

Astrophyllite, a rare mineral of the nephelite-syenites, has pleochroism, a = yellow to red, b = orange, c = citron-yellow. $2V = \pm 75°$, $2E =$ *ca.* 160°. It occurs in plates, laths along *b*, leaves, and rosettes. Cleavage (010) perfect. Micas have smaller axial angles and different pleochroism, and are negative. Låvenite is negative. Staurolite has lower birefringence and a different mode of occurrence.

Titanite, in the form of prisms, rhombs, and grains, is a very common mineral in acid plutonites, such as granites and syenites, abundant in nephelite-syenites, and less common in diorites. It is also abundant in some schists, gneisses, and limestones. As a secondary mineral (*leucoxene*) it is derived from titaniferous minerals. Pleochroism weak, $c > b > a$, in brown and yellow tones, $c:c = +39°$, and $2E = 45°$–$68°$. The strong dispersion produces colored isogyres. Monazite has lower birefringence, smaller extinction angle, and weak dispersion. Brookite has parallel extinction, $2V = 0°$ to $-23°$, and rutile is uniaxial.

Brookite occurs in veins with various other minerals such as albite, quartz, nephelite, rutile, garnets, etc., and in gold washings, always in the form of crystals. The acute bisectrix is normal to (100) but the axial plane is parallel to (001) for red and yellow, and parallel to (010) for green and blue. For red (670 $\mu\mu$) $2E = 58°0'$, yellow (589 $\mu\mu$) $2E = 38°10'$, yellowish green (555 $\mu\mu$) $2E = 0°$, green (535–525 $\mu\mu$) $2E = 21°40'$–$33°0'$ (*Manual*, p. 444, Figs. 619–23). The interference figure for white light is a combination of all of these (*Manual*, Fig. 624). Cassiterite and rutile have different habits, and brookite has very different strengths of double refraction in (100) and (010) sections.

The Mineral is Negative

Phlogopite is paler brown than biotite, reddish brown, or yellowish brown, sometimes greenish or colorless. 2V, as in biotite, is small to 0°. Biotite has stronger pleochroism, but when bleached may not be distinguishable from it. Phlogopite is essentially a mineral of marbles and crystalline dolomites, but does occur in the leucite rocks of Wyoming and in the mica-peridotites of southern Illinois. For separation from other minerals, see under muscovite.

Grünerite, a brown iron amphibole of fibrous, leafy, lamellar, or granular form, is a constituent of metamorphosed carbonate rocks whose chief or only carbonate is of iron. Pleochroism c = light brown, b = a = colorless. Amphibole cleavage separates it from other minerals, pleochroism and extinction angle (11°–15°) from other amphiboles.

Fayalite, the iron olivine, may be colorless or yellowish, greenish, reddish, with weak or no pleochroism in yellow and red tones. Olivine has $2V = 88°$ (fayalite, $2V = \pm 50°$), is optically positive, and has lower birefringence. Forsterite is positive, has $2V = 86°$, lower indices, and different occurrence (contact mineral in metamorphic limestones).

Aegirite, a constituent of sodium-rich igneous rocks, especially nephelite-syenites, phonolites, and leucitophyres, but also of some granites and syenites, occurs in the form of thin needles or crystals bluntly terminated. The pleochroism, a = deep green, b = lighter green to yellowish green, c = yellowish to brownish, and the extinction angle, $c:a = 3°–6°$, separate it from other pyroxenes; the pyroxene cleavage from other minerals. Acmite occurs in crystals with acute terminations and is brownish. Aegirite-augite has a large extinction angle.

Acmite occurs in long prismatic crystals with characteristic acute terminations. Occurrence same as aegirite. Color, brownish to reddish brown, often zonal around green centers of aegirite. Pleochroism, a = brown, b = light brown, c = greenish yellow. Extinction, $c:a = 3°–6°$. Aegirite has different pleochroism, and occurs in bluntly terminated crystals. Other pyroxenes have little or no pleochroism and larger extinction angles.

Piedmontite, a manganese epidote, occurs in glaucophane- and other schists, rarely in certain porphyries, for example, *porfido rosso antico.* Pleochroism, strong and characteristic, a = orange, b = violet, amethyst, c = red. The epidote-like character of piedmontite and its characteristic pleochroism, separate it from all other minerals.

THE DETERMINATION OF THE FELDSPARS

The general characteristics of all members of the feldspar group are the same. They are usually colorless, belong to the monoclinic or triclinic systems (with close resemblance in angles, twinning, etc.), have a cleavage of from 86° to 90°, a hardness of from 6.0 to 6.5, and a specific gravity of from 3.84 in celsian, through 2.55 in orthoclase, to 2.76 in anorthite.

They may be classified as follows:

Monoclinic	Composition	Triclinic
Celsian	$BaO \cdot Al_2O_3 \cdot 2SiO_2$	.....
Orthoclase	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	Microcline
Soda orthoclase	$(K, Na)_2O \cdot Al_2O_3 \cdot 6SiO_2$	Anorthoclase
.....	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	Albite
.....	$CaO \cdot Al_2O_3 \cdot 2SiO_2$	Anorthite

The twinning is one of the most important characteristics of the feldspars, and by the different extinction angles, the various members may be distinguished. The three most important kinds of twinning are C a r l s b a d , in which the composition plane is one parallel to the *c* axis, usually near (010), and the twinning axis the *c* axis; a l b i t e twinning in which the composition plane is (010) and the twinning axis normal to this face, and p e r i c l i n e twinning in which the *b* axis is the twinning axis and the composition plane is an inclined plane approximately parallel to the basal plane though tilted backward in albite and down in front in anorthite. All of these kinds of twinning may be combined in a single crystal, and they may be repeated many times to form the so-called polysynthetic twinning. When albite and Carlsbad twins are combined, the albite twinning may be recognized upon the (001) face by the fact that the elongation of the twinning lamellae lies in the direction of the faster ray, while in pericline twinning this length is the direction of the slower ray.

O r t h o c l a s e (Fig. 1) is negative, $b = c$, $a : a = \pm 5°$, extinction on (001) from (010) cleavage = 0°, on (010) from (001) cleavage = ±5°, 2V = 70° to 80°, 2E = 120° *ca.*, dispersion $\rho > v$, indices of refraction less than Canada balsam. The most common form of twinning in orthoclase is on the Carlsbad law. The twins are turned 180° with respect to each other. In the (001):(100) zone the extinction is parallel to the (010) cleavage and to the twinning line. When the twinning line shows on the (010) face, it makes an angle of 63°57′ (β) with the (001) cleavage and of ±21° with the extinction of each individual ($c : b = 19°–23°$). In this zone, as the sections depart from (010) and approach (100), the angle of the cleavage with the twinning line naturally increases from 63°57′ to 90°. The extinction angle also changes from 21° to 90°, the increase being slight at first, but, as the section approaches the (100) face, the change of extinction angle becomes very rapid. In any section in this zone the twinning line bisects the extinction angle and the cleavage.

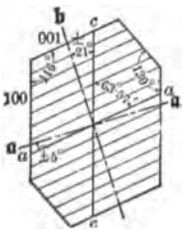


FIG. 1.—Section through a crystal of orthoclase, parallel to (010).

The (001):(010) zone of one individual of a Carlsbad twin almost coincides with the (101):(010) of the other. In all sections in this zone the cleavage cracks of one individual are parallel to the twinning line, and the extinction angle from this line varies from 0° on (001) to 3° to 7° (12° in soda-orthoclase) on (010). In the other individual the cleavage lines are at right angles to each other, and the extinction is parallel to them and to the twinning line. As the section approaches the (010) face, the extinction angle increases until it reaches ±48° on (010).

Baveno and Manebach twins are less common. In the former the twinning axis is the line normal to (021) which is also the composition plane. In sections at right angles to this plane, the

twinning line is diagonal to the cleavage. The two parts extinguish at the same time and are parallel to the cleavage, but the direction of a in one individual is at right angles to a in the other, and the interference figures lie at right angles to each other. Mannebach twinning is comparatively rare. The (001) plane is the composition plane and the twinning axis is a line at right angles to it.

Sanidine is like orthoclase in all its properties except that 2V is much smaller, varying from very small to 0°. The orientation may be different. It is either as in orthoclase or in some cases $b=b$, $a:a=+5°$, in which case the dispersion is $\rho<v$, otherwise $\rho>v$ as in orthoclase.

Microcline, chemically like orthoclase, is likewise negative. The extinction angle on $(010)=+5°$, on $(001)=+10°$. Indices of refraction, birefringence, and dispersion like orthoclase. $2V=71°$ to 84°. Combined polysynthetic twinning on albite and pericline laws is almost universally present, giving rise to a plaid effect or so-called "grating" texture.

Anorthoclase, negative, slightly higher in refractive indices but with the same birefringence as orthoclase, has the same dispersion, $2V=43°$–$53°$, extinction on $(010)=+4°$ to $+10°$, on $(001)=+1°$ to $+4°$. In some cases it is polysynthetically twinned on the albite and pericline laws like microcline, from which it is then separated by the extinction angles on (001) and (010), and by the smaller optic axial angle. It is separated from all plagioclases but albite by its low refractive indices; from albite by its optically negative character.

Plagioclase feldspars. The plagioclase feldspars form an isomorphous series. In this book the divisions are made as shown in the feldspar diagrams inside the back cover. The cleavage (001) to (010) is practically the same in all, varying from 86°24′ in albite to 85°50′ in anorthite. The angle β, between crystallographic a and c, is 116°29′ in albite and 115°55.5′ in anorthite.

All of the plagioclases are found in all kinds of igneous rocks, both plutonites and extrusives. It is to be noted, however, that only one kind of plagioclase of the same generation occurs in any igneous rock. The feldspar of a plutonite may be zonal, the more basic plagioclase in the center, and the zones progressively more acid toward the periphery, but two independent crystals of different plagioclases do not occur. It is true that a section cut through and parallel to the outer zone of a banded plagioclase may show nothing but acid plagioclase, for example, yet zonal growth in other crystals will show that the section was not cut from a crystal entirely of acid plagioclase. In the extrusive rocks the plagioclases of the phenocrysts and those of the groundmass may be, though they need not be, different, but they represent two generations; all of the material of each is of its own kind. The phenocrysts, having crystallized first, are usually the more basic.

Besides occurring in igneous rocks, albite occurs as a secondary mineral in gneisses and schists, and is also found disseminated through certain limestones. Anorthite has been found in meteorites and in slags.

Plagioclase is almost invariably twinned on the albite law and shows varying and characteristic extinction angles for each member of the group. Many methods for their separation have been proposed. The most useful of these are given below and are shown graphically, where possible, in the back of this book.

1. *By specific gravities.*—Curve A. The value of the specific gravity is constant so long as the material used is pure and unaltered. Glassy inclusions or alteration to kaolin reduce the value, while the inclusion of most other minerals or the alteration to carbonates, sericite, paragonite, or saussurite increases it.

2. *By the optical character of the mineral.*—Curve B. The optical character alone does not determine the kind of plagioclase, but it is of value when taken in connection with other properties. When the value of 2V is between 85° and 90° the curvature of the isogyre is too slight to be seen, consequently the position of the acute bisectrix (which is always on the convex side of the isogyre when it is placed at 45° to the cross-hairs) cannot be determined.

3. *By the relative indices of refraction of the feldspar and some known mineral with which it is in contact (Becke method).*—Curve C. When the feldspar lies in contact with a known mineral, their relative indices may be determined by the movement of the Becke line. By making use of several sections, the indices in different directions may be determined (*Manual*, pp. 277–83). The most common substance used for comparison is Canada balsam although its index varies slightly in different sections, depending upon age and the original solvent or amount of heat used in mounting. The index in good sections should lie between 1.534 and 1.540 (*Manual*, pp. 283–85). In this book the Canada balsam line is shown at the mean, 1.537. It is shown by the broken line in the figure. The lines ϵ and ω, shown in the same place, are the indices of quartz.

4. *By determining the refractive indices by immersion in various liquids.*—This method and a list of various immersion fluids are given elsewhere (*Manual*, pp. 249–65). The method has been very extensively used, and recently Larsen published a complete list of all minerals arranged according to their refractive indices (Bull. 679, U.S. Geol. Survey, 1921). Tsuboi, in a paper published in the Japanese language (*Jour. Geol. Soc. Tokyo*, Vol. XXVII, 1920), used the method in connection with cleavage flakes of feldspar, and gives the curves shown in D. These are of much greater practical value than those giving α, β, and γ.

5. *By extinction angles on cleavage flakes parallel to (010).*—Curve E. These values were determined by Schuster (*Tscherm. Min. Petr. Mitt.*, III [1880], 117). He considered extinction angles measured clockwise from cleavage on (010) and (001) as positive, and counter-clockwise as negative. The (010) face may be recognized by the fact that albite twinning lamellae are wanting, although those according to the pericline law are occasionally seen. The crystal form is often shown in outline or by zonal growth. The (001) cleavage is usually distinct, and is best seen when the diaphragm below the stage of the microscope is partially closed. In the acid plagioclases the elongation, as defined by cleavage, is nearly parallel to a. The extinction is measured from the (001) cleavage.

6. *By extinction angles on cleavage flakes parallel to (001).*—Curve F. These values were also determined by Schuster. Plates on (001) cannot be recognized in random fragments in rock sections, but must be obtained by crushing, not grinding, a fragment of the feldspar. Breaking along the cleavage, many of the flakes will be found to be parallel to (010) or (001). Only flakes of less than 0.5 mm. in thickness and with parallel faces (which may be recognized by their uniform interference colors) are of use. The (001) flakes show albite twinning, while those parallel to (010) do not. In the (001) sections the extinction is measured from the twinning lamellae.

7. *By the position of the bisectrix in (010) plates.*—(Becke, *Tscherm. Min. Petr. Mitt.*, XIV [1894], 375, 415; XVI [1897], 180.) In convergent light the different plagioclases show different positions of emergence of the bisectrix in (010) plates. In air they are as follows when the flake is oriented with the c axis vertical and the (001) face sloping from southwest to northeast:

In albite the inclination is small and the positive bisectrix (c) emerges below the center and slightly to the right. In oligoclase the bisectrix is nearly normal to the face but slightly above the center and to the left. In andesine the bisectrix lies nearly 20° to the top and left. In labradorite, upon the left face, the axis is not in the field; only part of a bar, part of one system of axial rings, and a small part of the lemniscate curves appear. The bisectrix lies off the field above and to the right. In bytownite the figure is similar to that in labradorite except that no lemniscate curves appear, only the circular rings about the melatope, which is off the stage but near the edge of the field in the southwest, are seen. The bisectrix lies to the northeast. In anorthite the melatope appears at the edge of the field at the southwest.

8. *By the extinction angles on sections cut at right angles to both (001) and (010).*—This method was used by Becker (*Eighteenth Ann. Rept. U.S. Geol. Survey*, III [1898], 34) and by Becke (*Tscherm. Min. Petr. Mitt.*, XVIII [1900], 556). Curve G. These sections are easily recognizable in microlites and in phenocrysts of extrusive rocks by their nearly quadratic sections, and in plutonites by zonal growths

with quadratic outlines. Sections at right angles to both (001) and (010) have the division lines between the albite twinning lamellae and the (001) cleavage lines extending at right angles to the section; consequently when the tube of the microscope is slightly raised or lowered, there will be no lateral displacement of these lines. The small cross-sections, shown at the side of the curve, indicate the directions of (+) and (−) extinction to a.

If the cross-section does not happen to be exactly at right angles to (001) and (010) it does not greatly matter, for the variation on tilting the section slightly is not great. This method is good where applicable, because the increase in the extinction angles from albite to anorthite is rapid and uniform.

9. *By the extinction angles on sections from the (001) (010) zone.*—(Extinction angles of microlites, after Wülfing, *Mikroskop. Physiog.*, I², 361–62.) Curve H. Spherulite rays and the microlites of the extrusive rocks are bounded by these cleavages. The curve above 12° is good if albite and andesine are separated by their refractive indices.

10. *By the extinction angles on sections at right angles to the optic normal* (b). Curve I. This is the method of Fedorow. The interference colors between crossed nicols of sections at right angles to the optic normal are the highest of any in that mineral, though rarely exceeding pale yellow in normal sections of feldspar. In the acid plagioclases, the extinction angles vary only from +2° to −2°, but from andesine to anorthite they change rapidly and may be used.

11. *By the extinction angles on sections at right angles to either bisectrix,* as used by Fouqué (*Bull. Soc. Min. France,* XVII [1894], 306). Sections cut at right angles to either bisectrix may be recognized by their intermediate birefringence. In convergent light the interference figure will close as a cross in the center of the field when the principal sections of the slide and nicols are parallel. Rotate the section to the diagonal position and test by the gypsum plate whether it is at right angles to the a or the c axis (negative or positive, disregarding whether the acute or the obtuse bisectrix appears in the field). In sections at right angles to a the extinction angle is measured from the twinning lines (solid line, Curve K). In sections at right angles to c, in the basic feldspars, the extinction angle is measured from the trace of the twinning lines or of the (010) cleavage (Curve M, dotted line). In the acid feldspars the section at right angles to c is very near the (010) face, and therefore shows neither twinning lamellae nor (010) cleavage; the extinction is measured from the (001) cleavage (Curve L, broken line).

Sections at right angles to a give good values as high as Ab_1An_1, and are of use when one can determine the positive or negative directions of extinction. The values in sections at right angles to c are good in the basic feldspars.

12. *By the extinction angles on sections from the zone at right angles to (010) or the symmetrical zone.*—(Statistical method of Michel-Lévy, *Ann. d. Mines,* 1877, pp. 392–471.) Curve N. Sections in this zone may be recognized by the fact that (1) albite-twinning lamellae are separated by very sharp lines which are not laterally displaced when the microscope is focussed, (2) the extinction angle from the twinning line is the same on each side, (3) if the section is turned to the 45° position the two systems of twins become of uniform interference color.

This method is one of the most valuable for the determination of the feldspars although some confusion may arise from the positive and negative directions of extinction in albite on the one hand and andesine on the other. The acid end, however, to about $Ab_{85}An_{15}$, in sections in this zone, has refractive indices less than Canada balsam, so the area of confusion falls entirely within oligoclase.

It is not necessary that the sections used be absolutely in the symmetrical zone, for there is but slight error if they vary no more than 10° or 15° from the true position. In such sections the extinction angles on either side of the twinning lamellae will not be the same, but half of the sum of the two angles very nearly coincides with the true values found in the zone. For determination, therefore, read the extinction angle of one twin at one side of the vertical cross-hair, turn the section past

the vertical cross-hair to the position of extinction of the other twin on the other side, and divide the angle thus obtained by two.

From albite to bytownite (extinction 45°), the extinction angles are read from the twinning lamellae to the intermediate vibration direction, but since a is nearly normal to the section, the third direction is near c, consequently the measured angle is toward the *faster* ray. For a short distance beyond the point where the extinction angle is 45°, the angle is read toward the other and *slower* axis of vibration. In anorthite, however, the nearest vibration direction is again the faster way.

13. *By the extinction angles on sections from the zone at right angles to (010), when the albite twinning is combined with Carlsbad twinning.*—(Michel-Lévy, *Étude sur la déterm. d. felds.*, Troisième fasc., 1904.) Occasionally the albite twinning is combined with Carlsbad twinning in the same section. In such cases the combined extinction angles are characteristic, without considering the direction of rotation, and it is not necessary to search for the maximum angle. A section is chosen which has approximately symmetrical extinction in the albite twins in each half of the Carlsbad twin. The angles are measured in each half as in the preceding method and divided by two. The angle of the smaller pair is found in the column to the left in Figure 23, the larger on the curves. The vertical line at the intersection gives the feldspar. In the figure the broken lines indicate the angles which the sections make with the (100) face. The size of this angle is indicated in the diagram by the figures which are not followed by the degree (°) mark.

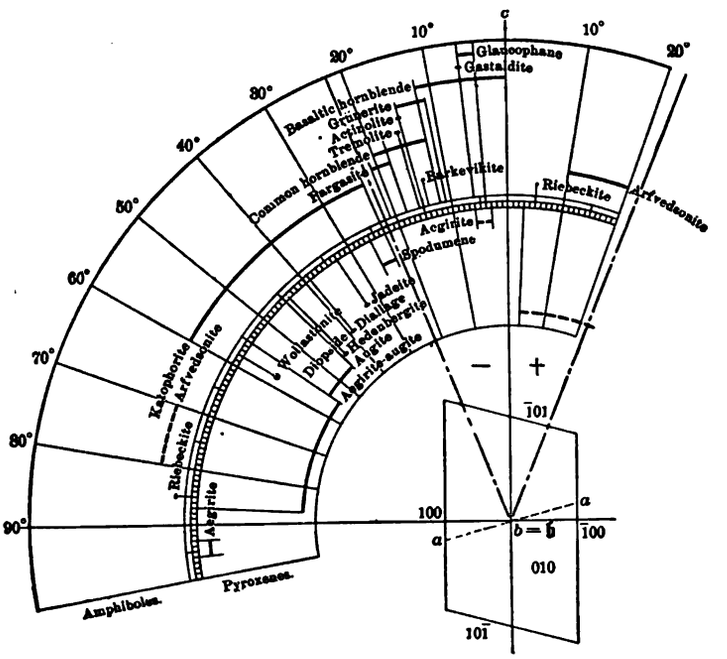


FIG. 2.—Maximum extinction angles in the Pyroxene and Amphibole groups. Solid lines indicate extinction angles from *c* to c; broken lines from *c* to a.

PYROXENES AND AMPHIBOLES

Pyroxenes differ from amphiboles in having a prismatic angle of 87° (amphiboles 124°), and generally less perfect cleavage. The crystals are usually stouter, the extinction angles are greater, and pleochroism is generally weaker, often wanting except in aegirite-augite, aegirite, and acmite. Augite, also, is sometimes quite strongly pleochroic in purple tones, and hypersthene in pink to green tones. The monoclinic pyroxenes are separated from the orthorhombic by having inclined extinction. Acmite, aegirite, and pectolite have extinction angles usually less than 5°, and may be confused with orthorhombic pyroxenes, except for their pleochroism. Besides differing in pleochroism, aegirite may be separated from orthorhombic pyroxenes by its much higher double refraction, and its negative elongation (all orthorhombic pyroxenes have positive elongation). Basal sections of orthorhombic sections in convergent light show the emergence of a positive bisectrix in the center of the field, monoclinic pyroxenes which have low extinction angles show a negative bisectrix, while the other monoclinic pyroxenes show the emergence of an axis. The chief mode of separation of the pyroxenes from each other is by means of extinction angles as shown by Figure 2. All pyroxenes are separated from other minerals by their characteristic cleavage.

PYROXENES

Name	System	Optical Character	Orientation	Optic Angle	Birefringence	Pleochroism
Enstatite	Ortho.	+	$c=c$	$2E=135°$	0.009	None
Bronzite	Ortho.	+	$c=c$	$2E=106°$	0.009	Faint
Hypersthene	Ortho.	−	$c=c$	$2E=85°$	0.013	Pink, green
Diopside	Mono.	+	$c:c=-39°$	$2V=59°$	0.029	None
Diallage	Mono.	+	$c:c=-39°$	$2V=59°$ and less	0.029	None
Hedenbergite	Mono.	+	$c:c=-44°$	$2V=60°$	0.015	Weak, green
Augite	Mono.	+	$c:c=-45°$ to $-55°$	$2V=60°$	0.025	May be purple
Aegirite-augite	Mono.	+	$c:c=-55°$ to $-87°$	.....	0.029	Green
Aegirite	Mono.	−	$c:a=-3°$ to $-6°$	$2V=62°$	0.050	Green
Acmite	Mono.	−	$c:a=-3°$ to $-6°$	.....	0.050	Brown
Spodumene	Mono.	+	$c:c=-23°$ to $-26°$	$2V=54°$ to $60°$	0.016	None
Jadeite	Mono.	+	$c:c=-33.5°$	$2V=72°$	0.029	None
Wollastonite	Mono.	−	$c:a=+32°$	$2V=40°$ to $69°$	0.015	None
Pectolite	Mono.	+	$c:a=-5°$	$2V=60°$	0.038	None

AMPHIBOLES

Name	System	Optical Character	Orientation	Optic Angle	Birefringence	Pleochroism
Anthophyllite	Ortho.	±	$c=c$	$2V=\pm 90°$	0.024	Yellow, brown, green
Gedrite	Ortho.	−	$c=c$	$2V=57°-79°$	0.021	Yellow, brown, green
Tremolite	Mono.	−	$c:c=-16°$	$2V=87.5°$	0.026	Non-pleochroic
Actinolite	Mono.	−	$c:c=-15°$	$2V=80°$	0.027	Faint green
Grünerite	Mono.	−	$c:c=-11°$ to $-15°$	$2V=82°$	0.045	Colorless, brownish
Common hornblende	Mono.	±	$c:c=-12°$ to $-20°$	$2V=54°$ to $84°$	0.016	Strong green, yellowish
Pargasite	Mono.	+	$c:c=-18°$ to $-21°$	$2V=52°$ to $60°$	0.019	Green, yellow
Katophorite	Mono.	+	$c:c=-23°$ to $-60°$	$2V=$small	low	Red, yellow
Basaltic hornblende	Mono.	−	$c:c=0°$ to $-12°$	$2V=80°$	0.021	Strong, green, brown
Barkevikite	Mono.	−	$c:c=-14°$	$2V=54°$	0.021	Brown
Glaucophane	Mono.	−	$c:c=-4°$ to $-6°$	$2V=50°$	0.018	Blue, violet, greenish
Gastaldite	Mono.	−	$c:c=-6°$	$2E=70°$	.....	Blue, violet, greenish
Riebeckite	Mono.	±	$c:c=-85°$	$2V=$large	0.005	Blue, yellowish green
Arfvedsonite	Mono.	∓	$c:c=+10°$ to $+20°$	$2V=$large	0.021	Blue to greenish

MODES OF OCCURRENCE OF VARIOUS MINERALS

Minerals which occur in needle-like crystals.—Actinolite, aegirite, apatite, aragonite, cancrinite, datolite, dumortierite, hydromagnesite, hydronephelite, natrolite, pectolite, sillimanite, stilbite, tremolite, topaz, tourmaline, wollastonite.

Minerals which occur in fibrous aggregates.—Chalcedony, datolite, gypsum, hydrargillite, kaolin, natrolite, prehnite, sericite, serpentine, sillimanite, talc.

Minerals which occur in radiating groups of fibers, or as spherulites.—Brucite, chlorite, chalcedony, delessite, natrolite, pectolite, quartz-orthoclase, stilbite, thomsonite, other zeolites.

Minerals which occur as cavity and interspace fillings.—Analcite, carbonates, chalcedony, quartz, sodalite(?), zeolites.

Minerals soluble in HCl without gelatinization.—Brucite, epistilbite, hematite (hot conc.), limonite (conc.), magnetite (conc.), monazite (conc.), pyrrhotite (conc.), stilbite.

Minerals which gelatinize with HCl.—Analcite, anorthite, cancrinite, chlorite, datolite, fayalite, glass, haüynite, hydronephelite, kaolin, laumontite, lazurite, leucite (part), melilite, nephelite, noselite, olivine, scapolite (Ca end), sodalite, wollastonite, zeolites.

Effervesce with HCl.—Calcite, cancrinite (slightly), dolomite (hot), hydromagnesite, magnesite (hot), siderite (hot).

Secondary minerals.—Albite (in metamorphic rocks), analcite, antigorite, brucite, calcite, cancrinite, chlorite, clinochlore, epidote, hematite, kaolin, leucoxene (titanite, etc.), limonite, magnetite, opal, paragonite, pennine, pyrite, quartz, rutile, saussurite, sericite, serpentine, talc, titanite, uralite (amphibole), zeolites.

Pneumatolytic minerals (frequently associated).—Fluorite, lepidolite, muscovite, topaz, tourmaline, zinnwaldite.

Metamorphic minerals by assimilation of other material in argillaceous rocks.—Almandite, andalusite, biotite, cordierite, corundum, disthene, ottrelite, pleonast, sillimanite, spinel, staurolite.

Metamorphic minerals by assimilation in calcareous argillites or argillaceous limestones.—Epidote, grossular, scapolites, vesuvianite, zoisite.

Metamorphic minerals by assimilation in calcareous rocks.—Calcite, datolite(?) wollastonite.

Metamorphic minerals by assimilation in magnesian rocks.—Actinolite, anthophyllite, brucite, diopside, forsterite, periclase, serpentine(?), talc(?), tremolite.

Other metamorphic minerals.—Graphite, magnetite, pyrite.

Minerals never secondary.—Apatite, cassiterite, eucolite, eudialyte, fluorite, haüynite, leucite, melilite, nephelite, noselite, pyrope, sodalite, tridymite, zircon.

Minerals never primary.—Chlorite, serpentine.

Never occur in igneous rocks.—Anhydrite, disthene, gypsum, ottrelite.

Rare yellow minerals of alkali-syenites and nephelite-syenites.—Astrophyllite, hjortdahlite, laavenite, lamprophyllite, mosandrite, rinkite, rosenbuschite. They are always accompanied by fluorite.

Minerals which usually give abnormal Berlin blue interference colors.—Chlorite, clinozoisite, melilite, vesuvianite, zoisite.

Alteration products which occur in minute shreds.—Kaolin, talc, white mica (paragonite, sericite).

Alteration products which occur in grains.—Albite, calcite, epidote, leucoxene, quartz, saussurite, titanite, zoisite.

Minerals which never occur together.—Quartz with nephelite, leucite, sodalite, haüynite, noselite, melilite, etc. Primary muscovite with pyroxene. Two different plagioclases of the same generation (see p. 31). Quartz is rare with olivine except in a few basalts.

Significant mineral association.—If aegirite, acmite, or golden brown biotite is present, you will frequently find nephelite, leucite, sodalite, analcite, etc. If one pneumatolytic mineral is present there are usually others also.

A SUMMARY OF PETROGRAPHIC METHODS

In the few pages following, reference can only be made to those points in the manipulation of the microscope which the occasional worker constantly needs and is likely to have forgotten.

Examination by ordinary light.—By ordinary light is meant light which is not polarized. As a matter of fact one uses plane-polarized light for practically all examinations which could also be made by ordinary light. Pleochroism only is affected (229–32[1]).

Without the analyzer, therefore, the microscope is tested and adjusted, and the vibration directions are determined in the accessories (229–32).

To determine the vibration direction of the slow ray in the accessories.—Obtain an interference figure in the mica plate. The line connecting the melatopes is the direction of c. Place the gypsum plate on the stage at 45° off extinction, and, with nicols crossed, insert the mica plate above it. If the interference color rises, the vibration rays of the two are parallel; if it falls, they are at right angles. Proceed in the same way with the quartz wedge.

Other determinations are crystal form (233), cleavage and parting (235), color (309–11), and refractive indices (237–85).

Becke line.—On r a i s i n g the tube of the microscope, the Becke line moves i n t o the medium having the h i g h e r index.

Examinations by plane polarized light.—In these examinations the analyzer (lower nicol) is in place, but the upper nicol is removed. Here are determined pleochroism (320–26) and refractive indices in different directions in a single mineral grain.

Determination of the vibration direction in the lower nicol (178).—A section of biotite cut at right angles to the cleavage has its greatest absorption, consequently is darkest, when its cleavage direction is parallel to the plane of vibration of the polarizer. Tourmaline, on the other hand, extinguishes light when its long direction (*c*) is at right angles to this direction.

Examinations between crossed nicols.—When a mineral is dark between crossed nicols it is i s o - t r o p i c (336), and may be a section of an isotropic mineral (isometric crystal or amorphous substance), or an isotropic section of an anisotropic mineral, that is, a section cut at right angles to an optic axis.

E x t i n c t i o n a n g l e s are measured between crossed nicols (339, 390–412). Crystals of the tetragonal, hexagonal, and orthorhombic systems show parallel extinction, that is, the principal vibration directions are parallel to the crystallographic axes.

It must be remembered that minerals of these systems which show prismatic cleavage may show a development of but one set of cleavage lines, for sections steeply inclined to the basal section (which shows two sets of cleavage lines) will show these lines forming an acute angle. If now the section is cut so that one set of lines is nearly at right angles to the section, the other will be nearly parallel to it, consequently in grinding, the mineral will be separated more or less along the former but not along the latter, with the result that a single set of lines, inclined to the extinction, appear. Usually at the same angle on the other side of the extinction, traces of the corresponding cleavage may be seen in the form of rough cracks or broken lines.

Furthermore, in minerals of these systems with prismatic cleavage, the traces of this cleavage are parallel or symmetrical with respect to crystallographic axes only in the zones at right angles to the three principal optic sections, that is, at right angles to the three planes containing the crystallographic axes. Interference figures on the sections in two of these zones will show a bar passing directly through the center of the field when the bar is horizontal or vertical, consequently they may be so identified. In other sections the bar when vertical or horizontal will lie off to one side. In all sections which cut the three crystallographic axes, the extinction will be inclined w i t h r e s p e c t t o t h e c l e a v a g e, the term parallel extinction referring, of course, to parallelism with the crystallographic axes and not with the traces of cleavage planes.

Another determination made between crossed nicols is b i r e f r i n g e n c e (348–59, 369–88). The interference color produced by a mineral depends upon two factors, thickness of section and difference between the refractive indices in two directions.

[1] The numbers in this section refer to pages in the writer's *Manual of Petrographic Methods*, 2d ed., New York, 1918.

This is brought out by the Michel-Lévy color chart shown in Figure 3. The numbers beneath the figure represent $M(n_2-n_1)$ in millionths of millimeters. The ordinates represent thickness of section. The value of unit birefringence, n_2-n_1 (that is $\gamma-\alpha$ or $\omega-\epsilon$) remains constant for any mineral, but as the section increases in thickness so does the retardation increase. The diagonal lines in the diagram represent, therefore, the retardation produced by sections of different thicknesses (371–72). Of course the interference color in a mineral depends also upon the orientation of the section, being zero or nearly zero along the optic axis and increasing to a maximum in the plane of the optic axes. To measure the maximum birefringence of a mineral, therefore, choose the section which gives the highest interference colors.

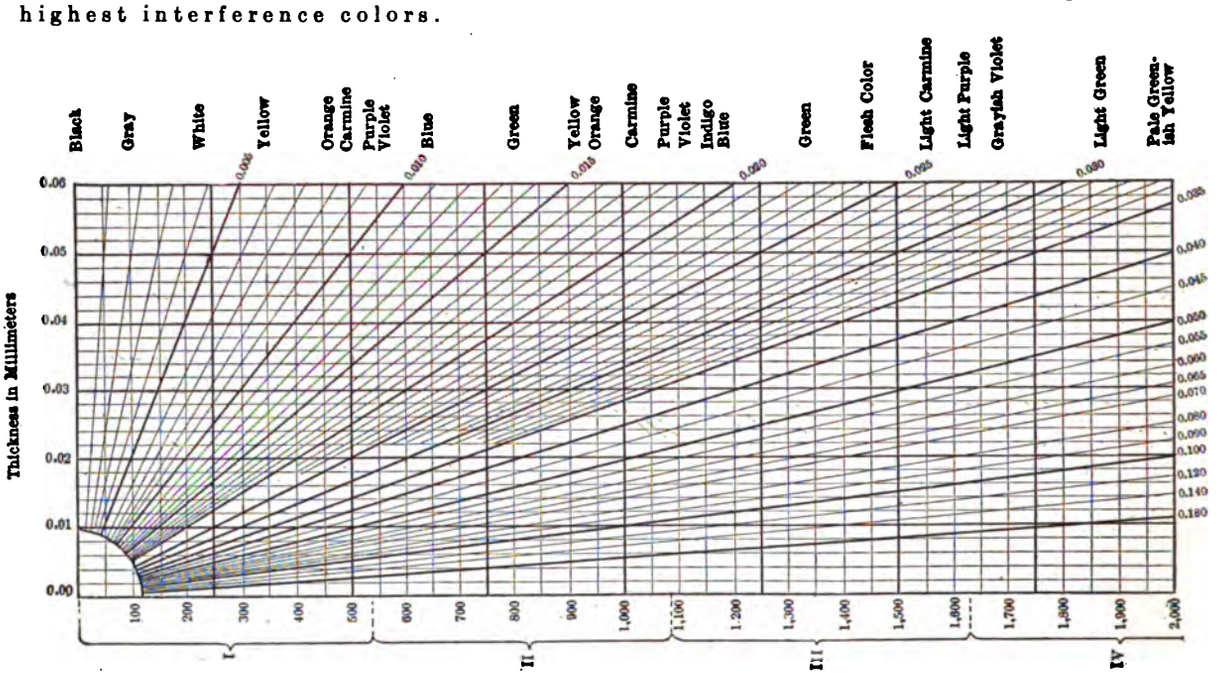


FIG. 3.—Outline of Michel-Lévy's chart of birefringences; the positions of the colors modified according to the Kraft scale for a clear sky.

The optical elongation is often useful in the separation of minerals (361).

Place the unknown mineral on the stage so that its vibration directions make angles of 45° with the vibration directions in the nicol prisms. The light is then at its maximum. Place above it, in the slot provided for the purpose, the gypsum plate (Red of the first order) or the quartz wedge, the former for low colors, the latter for high. If the interference color increases, the vibration directions are parallel, if it decreases, they are at right angles. It is usually well to determine the colors with the mineral successively in two positions at right angles to each other. From the known vibration directions in the accessory, it is thus determined whether the long direction (elongation) of the mineral is parallel to the fast or slow ray. If the elongation of the mineral is parallel to the direction of c, the mineral is said to have positive (+) elongation; if parallel to the fast ray, negative (−).

Examination between crossed nicols by convergent light.—By converting the microscope into a conoscope (413), it is possible to determine whether a mineral is isotropic, uniaxial, or biaxial. If it is isotropic (415) no interference figure is produced.

The student should familiarize himself with the interference figure produced by the microscope when set up properly as a conoscope but with only a blank object glass on the stage. All objectives give more or less well-defined uniaxial interference figures due to polarization by the glass of the objective or condenser (415). This should not be confused with the figure produced by uniaxial minerals.

In crystals of the tetragonal and hexagonal systems, a cross with a greater or smaller number of colored rings is produced (416–19, 425–26).

The section which will give the best interference figure with the cross in the center of the field is one which is completely isotropic between crossed nicols. If no such section can be found, choose the one giving the lowest interference colors. If the center of the cross lies only a little beyond the field of view, the fact that the mineral is uniaxial, or nearly so, is shown by the appearance of the bars which remain parallel to the cross-hairs during their passage

across the stage. The greater the distance from the center of the stage to the center of the cross, the greater the flare of the bar (418, Fig. 529). There is thus an apparent curvature.

Some idea of the strength of the birefringence may be obtained by the number of rings in the interference figure (422–23). This is sometimes of value, especially in colored minerals whose interference colors are hidden by the color of the mineral. Quartz, in a section of normal thickness (0.035 mm), with $\epsilon-\omega=0.009$, shows a black cross and the first yellow ring at the periphery of the field of view. Biotite with $\gamma-\alpha=0.040$, gives two colored rings, and calcite, with $\omega-\epsilon=0.172$, gives too many to count.

In crystals of the orthorhombic, monoclinic, and triclinic systems, the interference figures are biaxial (420–24, 426). Unless the optic axial angle is very small, only a portion of the figure can be

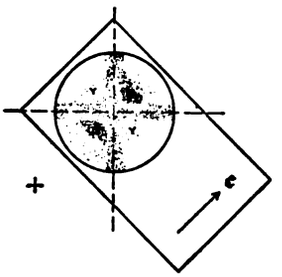


FIG. 4.—Quartz (+) under a gypsum plate.

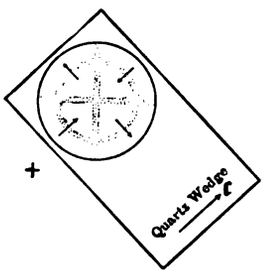


FIG. 5.—A positive uniaxial interference figure. The arrows indicate the movement taking place upon inserting a quartz wedge above the section.

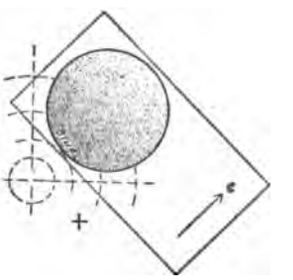


FIG. 6.—Quartz (+), with the center of the cross outside the field of the microscope, as seen under a gypsum plate.

seen. The average microscope will show the two melatopes of topaz just at the limits of the field ($2E=130°$ *ca.*).

For the determination of the uniaxial or biaxial character, a figure with both bars off the stage may suffice, but to determine the optical character, it is necessary (unless the optic axis be measured) that a melatope remain in the field of view during a complete rotation of the stage, for the melatope is at its greatest distance from the center in the 45° position, which is the position in which the curvature of the bar is to be determined. In the 45° position the convex side of the bar is toward the acute bisectrix. For the determination of the optical character, therefore, it is not the most symmetrical figure (at right angles to a bisectrix) which is best, but the one most nearly at right angles to an optic axis. Since light is dispersed in all biaxial crystals, such a section can be actually at right angles to an optic axis only for a given color, consequently is never actually isotropic. As in uniaxial crystals, so here also, the section giving the lowest color gives the best figure for the determination of the optical character.

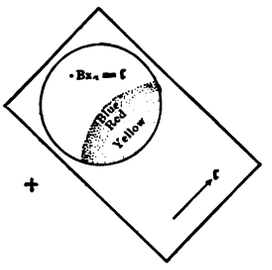
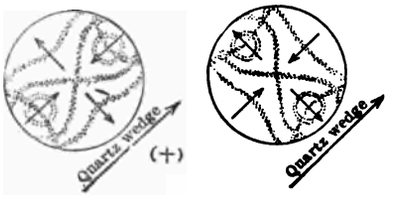


FIG. 7.—The appearance of a biaxial positive (+) crystal, showing one melatope in the field, under a gypsum plate.



FIGS. 8–9.—Movement of the colors upon inserting a quartz wedge above the interference figure of a positive (+) biaxial mineral. The lower arrows indicate the direction of c in the wedges.

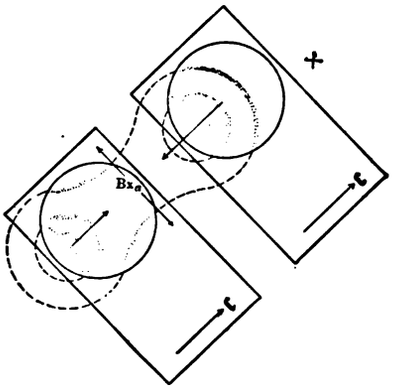


FIG. 10.—A biaxial interference figure seen in two positions, each field showing the emergence of an optic axis. The arrows indicate the movement taking place upon inserting a quartz wedge above the section. The mineral is augite (+).

The optical character of both uniaxial (457–62) and biaxial (462–65) crystals is obtained, as just mentioned, in sections which show the emergence of an optic axis. The determinations may be made by means of various accessories, the ones most commonly employed being the gypsum plate and the quartz wedge.

If one considers a uniaxial crystal as only a special case of a biaxial in which the optic axial angle is 0°, or considers the biaxial as a special case of the uniaxial in which the axis has been split apart, one need only remember the phenomena in two cases. Figure 4 shows a uniaxial interference figure with the emergence of the optic axis in the center of the field. In a positive mineral, with the gypsum plate orientated as shown in the figure, the blue spots appear in the northeast and southwest quadrants. (If the orientation of the slow ray in the gypsum plate is at right angles to that shown in the figure, the phenomenon is, of course, reversed, and yellow appears in the northeast, etc., quadrants.) Figure 5 shows the phenomenon appearing when a quartz wedge whose slow direction vibrates across the accessory is pushed across a positive uniaxial figure. One needs but remember that the colors in the southeast quadrant move toward the hand. (With negative minerals or with the orientation of the slow ray in a different direction in the wedge, the phenomenon is reversed.)

All other cases can be reduced to these two. Thus Figures 6 and 7 are the same as Figure 4, and Figures 8, 9, and 10 the same as Figure 5.

Measurement of the optic axial angle.—The methods for measuring the optic axial angle should be looked up elsewhere (466–502).

A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS

The main division lines in the classification of igneous rocks which is generally accepted are the result of a gradual development through the hundred and twenty years during which were produced the systems of Werner (1787), von Leonhard (1823), Zirkel (1866 and 1894), and Rosenbusch (1877, 1887, 1897, and 1907–8). All of these systems were qualitative and more or less mineralogical, but they lacked the quantitative element now deemed essential. As a consequence, rock terms have been used loosely or with different meanings. Thus dolerite, originally applied to a coarse basalt, has been used for any dark rock, and in England is used for rocks which we call diabase. The term diabase in the United States means a dike-rock with an ophitic texture, yet it was originally used for Paleozoic basalts and is still so used in various countries. Basalt has been applied to plagioclase rocks with augite and olivine and irrespective of the kind of feldspar, to labradorite-pyribole rocks with or without olivine, to the darker labradorite-pyribole rocks, to post-Tertiary extrusives of gabbroic magma, etc.

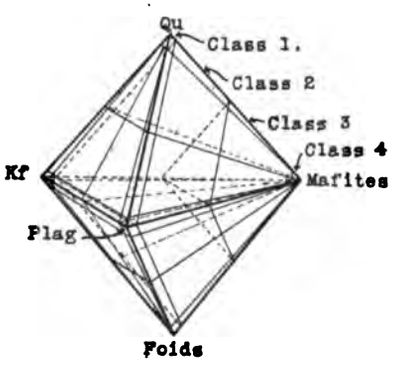


FIG. 11.—Subdivisions of the double tetrahedron into classes, representing light to dark rocks.

The system to be presented here[1] is strictly mineralogical, quantitative, and modal, and is directly applicable to all plutonites and to practically all extrusives. No attempt has been made to change the general basis of classification of the old system, although the additional factor of the ratio of the dark to the light constituents is used.

As an objection to a quantitative mineralogical system, it will be said that it is not always possible to determine the exact composition of rocks with glassy bases, or extrusives of the alkali series. But the percentage of indeterminable rocks is comparatively small, and for these there still remain, if necessary, chemical methods for determining the composition of the base. Most glassy rocks are leucocratic, and a recalculation into the minerals which would have crystallized had the conditions been right is easy.

The basis of the classification here proposed is a double tetrahedon (Fig. 11), each trihedral angle of which represents certain mineral constituents. Since there is no geometrical figure having

[1] This classification of igneous rocks has been gradually developed by the writer since 1909, and is described in considerable detail in the following papers, to which the reader is referred:

"Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 63–97. Figs. 27.

"A Quantitative Mineralogical Classification of Igneous Rocks, Revised," *ibid.*, XXVIII (1920), 38–60, 159–77, 210–32. Figs. 7.

as many corners as there are minerals in the rocks, it was found necessary to divide the minerals into certain groups. Since quartz and the feldspathoids never occur together, it is possible to make the classification in five dimensions by using two tetrahedrons with a common base.

The groups of minerals represented by the corners of the double tetrahedron are (1) quartz (symbol Qu[1]); (2) potash feldspars, including also anorthoclase, microperthite, etc. (symbol Kf), (3) all plagioclases, (4) all feldspathoids, (5) the mafites,[2] including the ferromagnesian constituents, the "ores," etc., as given below.

As shown in Figure 11, the double tetrahedron is unsymmetrically divided by the traces of planes, some parallel to the quarfeloid[3] face, others converging to one of the angles. The divisions were so made to conform to the rock names of the older classifications. It is true that new names might have been devised for symmetrical subdivisions, but it was not thought desirable to discard entirely the old and well-tried lines of separation which have very much to recommend them besides the fact that they have been so long in use. The old classifications are unsymmetrical, for we speak of a rock as a quartz-syenite, quartz-monzonite, quartz-diorite, etc., when it contains any amount of quartz. With respect to this mineral, therefore, the classification is based upon its ratio to the sum of all the other constituents, and the lines of division must be parallel to the side of the tetrahedron. The same is true also of the feldspathoids. In the divisions according to the feldspars, however, we find for example that a rock is a quartz-monzonite whether the total feldspar percentage is 10 or 90. Here the divisions are based upon the ratio of the feldspars to each other, irrespective of what their amount may be in the rock. The division lines, therefore, must converge toward the quartz and feldspathoid corners, as shown in Figures 11, 15, etc.

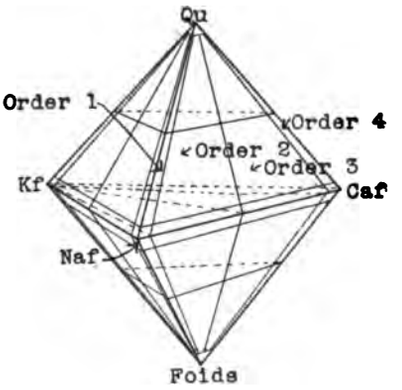


FIG. 12.—Subdivisions of the secondary double tetrahedron into orders, representing differences in the kind of plagioclase.

Classes.—The igneous rocks may be divided into various classes according to the percentage of dark constituents present. Four divisions are here made: (1) rocks with less than 5 per cent of dark constituents, (2) dark constituents between 5 and 50 per cent, (3) dark constituents between 50 and 95 per cent, and (4) dark constituents more than 95 per cent. Since these division lines represent planes parallel to the two quarfeloid planes (quartz-feldspars and feldspars-feldspathoids), Figure 11, they form similar double triangles whose sizes represent the amounts of light constituents, consequently decrease with increase in dark constituents and with approach to the mafite corner. For convenience, however, since they are similar, they may be represented by triangles of the same size.

Orders.—Thus far the classification is one of five dimensions. But this is not enough. The kind of plagioclase in the rock must be taken into consideration. Imagine that the lozenge-shaped quarfeloid plane consists of two sheets of paper fastened together only along the Qu-Kf-Foids edge. If now the loose corners at the right of the two sheets be separated a distance equal to a side of the original

[1] In the figures following, the quartz corner is indicated by the symbol Qu. The letter *f* is used for feldspar, therefore Kf indicates the potash-feldspars—orthoclase, microcline, anorthoclase, microperthite, etc. Naf indicates albite, Ca*N*af represents the acid plagioclases, Na*C*af the basic plagioclases, and Caf anorthite. In Ca*N*af and Na*C*af, the element in excess is indicated by italics and the symbols are to be read, calcium-bearing soda-feldspar, and soda-bearing calcium feldspar. Foids is the symbol used for the feldspathoids.

[2] The term mafite is here used for the dark minerals of a rock. This term includes not only the mafic (ferromagnesian) minerals of C.I.P.W., but certain iron minerals listed below, as well.

[3] Quarfeloids (QUARtz, FELdspar, feldspathOIDS) is used as a noun for minerals in the front faces of the double tetrahedron, "felsite" being unavailable from its use as a rock name. "Leucocrates" cannot be used, since all light-colored minerals are not included.

triangle, a new double tetrahedron will be developed, the horizontal line along which it was opened representing all plagioclases, the ends being formed by the Ab and the An molecules (Fig. 12). The same thing is done in each of the first three classes, the fourth being differently divided as shown below. The classification will now be made up of three double tetrahedrons (and a single tetrahedron for the fourth class), one for each class, the corners being formed by quartz, potash feldspar (including microperthite, anorthoclase, etc.), albite, anorthite, and the feldspathoids. But these tetrahedrons may be subdivided into orders, depending upon the proportions of the albite to the anorthite molecule; consequently the divisions must be made by planes all of which cut the quartz-potash-feldspar-feldspathoid edge but which separate across the central plane of the double tetrahedron as shown by the dotted lines in Figure 12 and by Figure 13. The edge Qu-Kf-Foids remains common to all of the divisions, the plagioclase corner simply having been changed. Now while the triangles formed by the intersections of these planes with the tetrahedron are not all equilateral, the relative position of any rock plotted on any intersecting plane is the same as it would be in the equilateral triangle, since the divisions are 100 each way in every possible triangle. Equilateral triangles, consequently, may

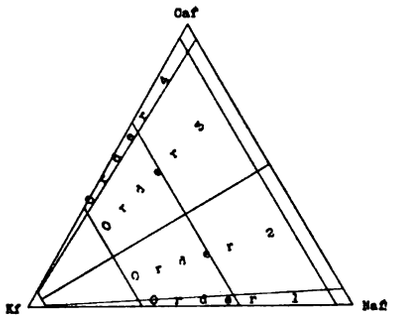


FIG. 13.—A section through the central plane of Figure 12.

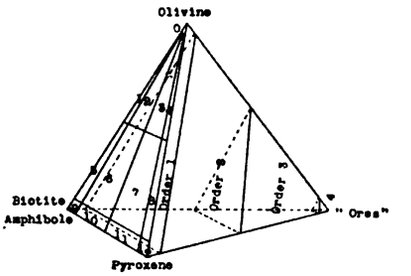


FIG. 14.—Subdivisions of the single tetrahedron of Class 4 into orders.

be substituted for any triangle. In this manner the different orders may be represented by a series of double equilateral triangles whose right-hand corners vary with the kind of feldspar. Figures 16–19 show the plutonic rocks in Class 2.

Each of the first three classes is hereby divided into orders according to the Ab-An ratio in the plagioclase. The division points are $Ab_{100}An_0$, $Ab_{95}An_5$, $Ab_{50}An_{50}$, Ab_5An_{95}, Ab_0An_{100}. There are thus formed, for each class, four double triangles in each of which three angles represent (1) quartz (Qu), (2) all feldspars except plagioclase (Kf), and (3) the feldspathoids (Foids). The remaining angle (Plag) represents albite (Naf) in Order 1, oligoclase to andesine (Ca*Naf*) in Order 2, labradorite to bytownite (Na*Caf*) in Order 3, and anorthite (Caf) in Order 4, making the divisions conform to the present lines of separation between the alkali rocks, the acid plagioclase (dioritic) rocks, the basic plagioclase (gabbroic) rocks, and the anorthite rocks. Figures 16–19 represent the triangles of Class 2. There are similar sets for Classes 1 and 3. Zonal feldspars may be determined by considering the approximate amounts of each kind and obtaining the average Ab-An value. This will be necessary in but few cases, for ordinarily a simple inspection will show whether the average runs across the $Ab_{50}An_{50}$ line. Of course if the nucleus as well as the rim falls entirely between the 0 and 5, 5 and 50, 50 and 95, or 95 and 100 lines, there is no need for computation.

Class 4: Owing to the practical absence of light constituents in Class 4, the subdivisions into orders must be made on a different basis from those of the first three. They are here made by dividing the tetrahedron by planes parallel to the left-hand face, forming four orders, depending upon the amount of ores present (Fig. 14). The division points for these planes, as in the other classes, are 0-5-50-95-100.

There are now six dimensions in the classification, and since each pigeonhole will represent not only a plutonic rock but also a hypabyssal and an extrusive, we may say we have a classification in

seven dimensions, yet every rock is shown by a single point on a drawing in a single plane. The more detailed description which follows may make this clearer.

Families.—The quarfeloid face of the double tetrahedron will appear as shown in Figures 16–19. The families in the first three classes are to be numbered as shown in Figure 15. The object of beginning with 0 is to make the positions easier to remember, since they run in groups of four. The division points are at 0-5-50-95-100 on both the feldspar base line and in the vertical direction, except for the few intermediate monzonitic families to be mentioned in a moment. Families 0, 1, 5, 9, 13, 17, 21, and 25 occur but once in each class, since the amount of plagioclase in each, whether albite, acid plagioclase, basic plagioclase, or anorthite, is too small to make an essential difference in the rock. They form the hinge about which the order tetrahedron (Fig. 12) was opened, and are the same in all orders. For convenience these "hinge families" are classed with Order 1. This is shown in Figures 16–19 where these families are omitted and are represented by dotted lines.

In the original article describing this classification there were thirty-two families, an intermediate family having been inserted along the $Ab_{50}An_{50}$ line, namely, the family of the monzonites. Since in general descriptions these monzonitic rocks are unnecessary, they are omitted from all orders. For special rock descriptions the additional monzonitic families, adamellite and monzonite, are used as shown in Figure 15. Certainly the intermediate families are not necessary between Families 2 and 3, 22 and 23, and doubtfully between 14 and 15, and 18 and 19. Whether they are used or not need cause no confusion, the rock names[1] as indicated show what divisions have been made. That these are smaller families is shown even in the numbers by the marks (′) and (″) after them. They may thus be used or not as desired.

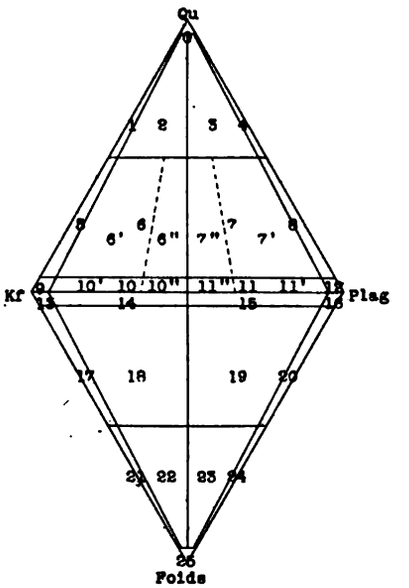


FIG. 15.—Family numbers in Classes 1–3.

Class 4: The single tetrahedrons of the four orders of Class 4 are subdivided on the basis of the dark minerals present since the light-colored constituents are practically wanting. In Orders 1, 2, and 3, of Class 4, the corners represent respectively olivine, biotite and (or) amphibole, and pyroxene (Figs. 14 and 20). In Order 4, if thought desirable, they may be taken to represent the various ores: the writer, however, groups these in one family, for, considered as rocks, they are unimportant. The various hematite, magnetite, ilmenite, etc., ores may be made subfamilies.

THE MINERAL GROUPS

The constituents of the rock are divided into three primary groups:

QUARFELOIDS

(Qu) Quartz
(Kf) Orthoclase, microcline, microperthite, anorthoclase, etc.
(Plag) The whole isomorphous Ab-An series of plagioclases
(Foids) The feldspathoids (nephelite, leucite, sodalite, haüynite, noselite, melilite, primary analcite, etc.)

[1] Granodiorite is given the original significance intended by Lindgren, being applied to a rock intermediate between granite and diorite. Syenodiorite, as originally used by the writer, is the quartz-free equivalent. In the limited sense rocks between adamellites and quarts diorites are called monzotonalites, and between monzonites and diorites monzodiorites. On the granite side the limited granite, between orthogranite and adamellite is monzogranite, and between monzonite and orthosyenite, monzosyenite. The name indicates at once its intermediate position.

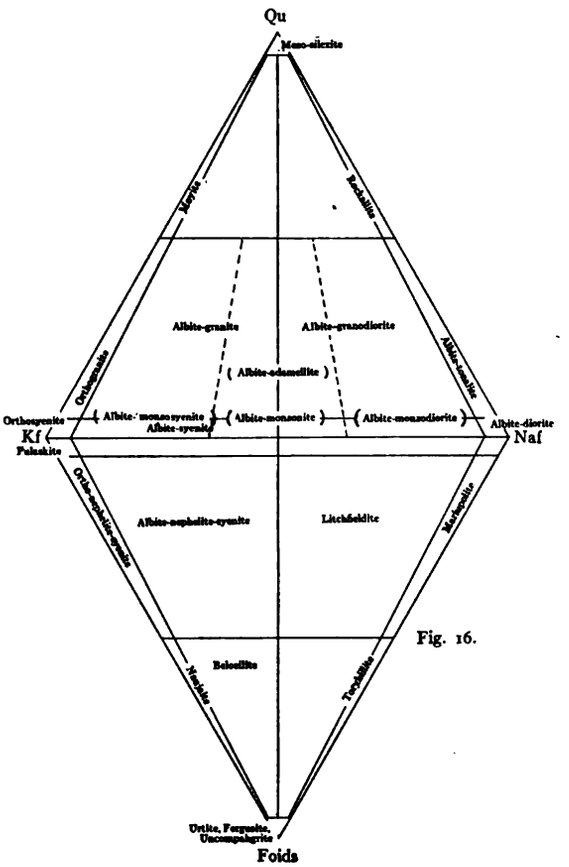


Fig. 16.

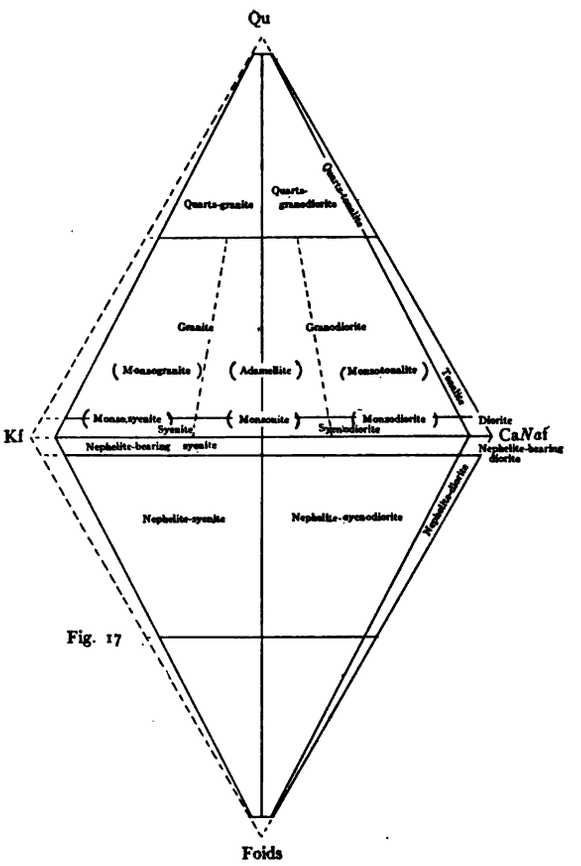


Fig. 17

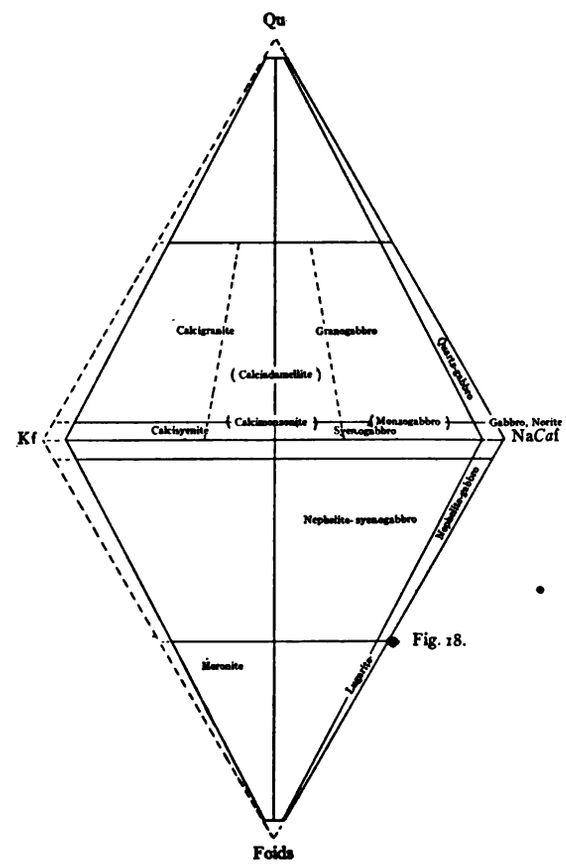


Fig. 18.

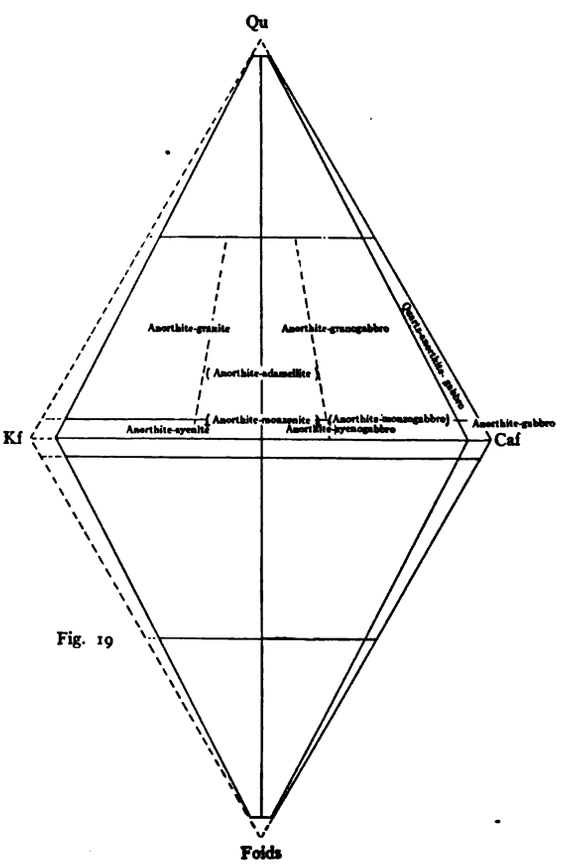


Fig. 19

MAFITES

Dark micas (biotite, phlogopite, zinnwaldite, etc.)
Amphiboles
Pyroxenes (including uralitized pyroxene)
Olivine
Iron "ores" (magnetite, ilmenite, chromite, pyrite, hematite, etc.)
Cassiterite
Minor Mafites { Garnet; Primary epidote; Allanite, zircon, rutile, primary titanite, spinel, and other dark minor constituents

AUXILIARY CONSTITUENTS

The auxiliary constituents are seldom of importance.

Topaz	Corundum	Primary scapolite	Lepidolite
Tourmaline	Fluorite	Primary calcite	Apatite,
Cordierite	Andalusite	Muscovite	etc.

Most of the auxiliary constituents are light in color; they are, consequently, computed among the leucocrates.

SECONDARY CONSTITUENTS

Secondary constituents are to be calculated as the originals from which they came. Thus ore replacements of the mafites are computed as mafites, kaolin as feldspar, etc., chlorite as a biopyribole, analcite as feldspathoid, pseudoleucite as leucite, etc.

GLASS

Glass must be computed from an analysis. One can usually surmise its composition from the character of the phenocrysts and the appearance of the rock as a whole. When undetermined, the rock must be given a tentative name, such as hyaline-rhyolite, etc. Glassy rocks are rare.

RULES FOR COMPUTING ROCKS FROM THEIR MODES

1. The sum of the minerals in the mode should be 100 ± 0.5. If greater or less, it should be recalculated to 100. The sum of the leucocrates (quarfeloids plus auxiliary minerals) determines the class.

Class 1. Leucocrates form more than 95 per cent of the total components
Class 2. Leucocrates between 95 (inclusive) and 50 per cent
Class 3. Leucocrates between 50 (inclusive) and 5 per cent
Class 4. Leucocrates between 5 (inclusive) and 0 per cent

2. Determine the orders in Classes 1, 2, and 3 directly from the Ab-An ratio in the plagioclase.

Order 1. $Ab_{100}An_0$ to $Ab_{95}An_5$
Order 2. $Ab_{95}An_5$ (inclusive) to $Ab_{50}An_{50}$
Order 3. $Ab_{50}An_{50}$ (inclusive) to Ab_5An_{95}
Order 4. Ab_5An_{95} (inclusive) to Ab_0An_{100}

In Class 4 the orders are determined by the percentage of "ores." Reduce the sum of biotite, olivine, pyribole, and "ores" (including cassiterite, chromite, etc.) to 100, dropping the minor mafites, apatite, garnet, perofskite, any small amount of quarfeloids, etc. The percentage of "ores" determines the order.

Order 1. 0 to 5 per cent "ores"
Order 2. 5 (inclusive) to 50 per cent "ores"
Order 3. 50 (inclusive) to 95 per cent "ores"
Order 4. 95 (inclusive) to 100 per cent "ores"

3. Determine the family. In Classes 1, 2, and 3, first recalculate the quarfeloids to 100. The amount of quartz (or feldspathoid) thus determined immediately locates a row of horizontal pigeonholes, in one of which the rock belongs. Recalculate Kf plus plagioclase to 100 and determine the proper point on the Kf-Plag base line. This determines the vertical series of pigeonholes, and its intersection with the horizontal series gives the proper position for the family. Still simpler is the location of the family graphically. This is discussed below.

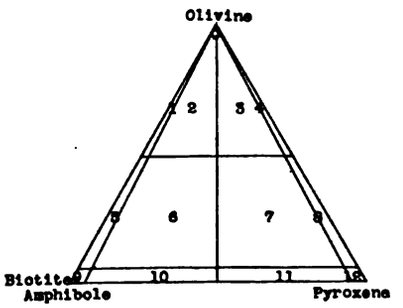


FIG. 20.—Family numbers in Class 4

In Class 4, Orders 1, 2, and 3, recalculate the olivine, pyroxene, and biotite plus amphibole to 100 (Fig. 20) and find the position by taking the relation of olivine to the sum of the biotite and pyriboles for the horizontal line, and of biotite plus amphibole to pyroxene for the intersecting line. Graphically the method is the same as for the other classes.

4. *Subfamilies.*—In all classes, subfamilies are based on 0-5-50-95-100 division points after the manner shown in Figure 21. Thus we may have biotite-granite, hornblende-bearing biotite-granite, biotite-bearing hornblende-granite, and hornblende-granite.

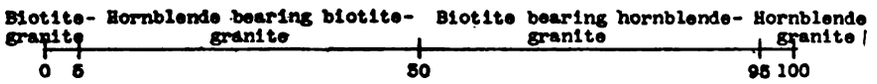


FIG. 21.—Method of naming subfamilies

A FEW POINTS TO BE OBSERVED

A rock whose percentage value falls exactly on a family line should be given the name of the family in the pigeonhole toward the opposite apex of the triangle, except as indicated below. Thus a syenite with 5 per cent quartz is called a granite. On the 50-50 line of quartz they are moved upward, and on the 50-50 line of foids downward, toward the apices; that is, they are placed in Families 1–4 or 21–24. On the 50-50 line between Kf and Plag they are included in the Plag side. Rocks falling on the line separating the two triangles, namely, on the feldspar base line, usually should be classed on the quartz side, that is, on the normal side, but if the rock has affinities with alkalic rocks, it should be placed on the Foid side.

For classificatory purposes, it is seldom necessary to make exact determinations of the mineral percentages. Unless the proportions are such that the rock falls near a division line, a simple inspection will answer.

EXAMPLE

A granodiorite having the composition:

Quartz	14.0	= 18.7		
Orthoclase	15.0	= 20.0	= 24.6	
Oligoclase ($Ab_{90}An_{10}$)	46.0	= 61.3	= 75.4	
Total quarfeloids		75.0	100.0	100.0
Biotite	12.0			
Hornblende	12.0			
Magnetite	0.6			
Titanite	0.4			
Total mafites		25.0		
		100.0		

Percentage quarfeloids = 75. The rock belongs to Class 2.

$Ab_{90}An_{10}$ falls between 95 and 50. The order, therefore, is 2.

The family, with 18.7 quartz (light constituents reduced to 100), falls in the row of families 5 to 8 The ratio orthoclase to oligoclase is 24.6 to 75.4, consequently the family is 7, granodiorite. If the monzonitic families are included, it is 7′, monzotonalite. The rock number is 227 (or 227′), to be read two, two, seven (or two, two, seven prime).

Graphically[1] the rock may be shown by a point and a line as indicated in Figure 22. Draw three lines, parallel to the sides of the triangle, through the points representing the amounts of the corner minerals in the rock. In this case a horizontal line through 14 for quartz, a line sloping northeast and southwest through 46 for oligoclase, and a line sloping northwest and southeast through 15 for orthoclase. Lay the side of a straight-edge on the apices of the two triangles and draw a short line through the small triangle from its apex to its base. Connect either of the lower corners of the large triangle with the similar corner of the small one, and indicate its intersection with the line first drawn by a dot, *F*. The line *bd* and the spot *F* represent the rock. The point *F* is the same as that which was obtained by computation above. It gives the relative proportions of the light constituents, quartz (mF), orthoclase (kF), and plagioclase (iF), in the rock by its distances from the sides of the triangle opposite these names at the corners. The actual percentages of the minerals in the rock are also represented: *bc* or *pk* for orthoclase, *ab* or *io* for plagioclase, *bd* for the dark constituents, *dm* for quartz.

In a similar manner the composition of the rock at *L* may be read directly from the diagram, giving the values:

Quartz	23 =	27.7
Orthoclase	45 =	54.2
Andesine	15 =	18.1
Total quarfeloids	83	100.0
Dark constituents	17	
	100	

Class 2, Order 2, Family 6′ (normal granite = 6, or monzogranite = 6′).

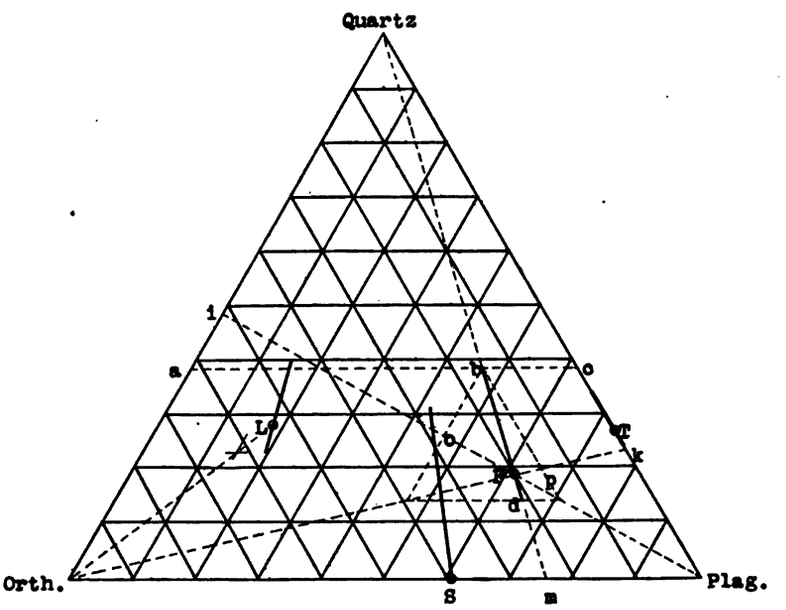


FIG. 22.—Method of graphical plotting of rocks

The rock at *S* is seen to consist of orthoclase 27 per cent, plagioclase 42 per cent, quartz 0 per cent, and dark minerals 31 per cent. The relative ratios of the light constituents are: orthoclase 39.1 per cent, plagioclase 60.9 per cent, and quartz 0 per cent. The rock at *T* consists of orthoclase 0 per cent, plagioclase 66 per cent, quartz 24 per cent, dark constituents 10 per cent. Relative ratios of the light minerals, plagioclase 73.5 per cent, quartz 26.5 per cent, and orthoclase 0 per cent.

The actual plotting takes much less time than the telling. In fact the small triangle is never drawn. The upper end of the line is located at the dividing point between orthoclase and plagioclase on the horizontal line whose length is equal to the sum of the feldspars, and through this point the inclined line is drawn to the percentage position of quartz. One of the lower corners of the small triangle is located, without drawing it, and the intersection of the inclined line with the ferromagnesian mineral line is used to determine the locus of the rock.

[1] See the writer's "On the Representation of Igneous Rocks in Triangular Diagrams," *Jour. Geol.*, XXX (1922), pp. 167–69.

NAMES PROPOSED FOR VARIOUS FAMILIES

On the basis of the foregoing subdivisions, many modal analyses have been plotted and names[1] have been given to many of the families, most of them derived from plutonic rocks falling at the center points. In some cases, as in the quartz-rich types, family names were taken from differentiation rocks. In the tabulation following, there are many blank pigeonholes, owing to lack of good modal descriptions. There are undoubtedly many rocks in most of the families here left blank, especially in Classes 2 and 3, but the majority of published rock descriptions lack mineral percentages, making them unavailable for classification. Blank spaces in the tables do not necessarily mean that rocks are wanting in these pigeonholes, but may indicate that none falls near the center point, although, on the other hand, a solitary rare rock may, in some cases, give its name to the family, even though it is not at the center.

A certain system is used for the prefixes. The terms "granite," "syenite," "diorite," etc., are defined, and the addition of a prefix to any one indicates a definite modification. Where no specific names are available, "leuco-" is used to indicate rocks of Class 1, "meso-" those of Class 2, and "mela-" those of Class 3. In most cases the prefix "meso-" is unnecessary, since normal rocks belong to Class 2, and these are written without the prefix, the class being understood. Thus there are leuco-granites, granites, and mela-granites, respectively, in Classes 1, 2, and 3.

Analogous rocks in the four orders of each class similarly have distinctive prefixes where no other names are available. The rocks of Order 1 have albite as their plagioclase; therefore an albite-monzonite is a monzonite whose plagioclase is albite, and in Order 4 an anorthite-monzonite is one containing orthoclase and anorthite. An albite-diorite means a rock all of whose plagioclase is albite, since a diorite contains only plagioclase; an albite-granite, on the other hand, means a granite containing some albite in addition to orthoclase, since granite itself is defined as a rock consisting of quartz, a biopyribole, orthoclase, and less plagioclase. That is to say, the term "granite" in itself conveys the idea of an orthoclase rock with some plagioclase, the latter indicated, except in normal rocks, by the prefix. The plagioclase in Order 2 is oligoclase to andesine, and that of Order 3 labradorite to bytownite. Acid and basic cannot be used as prefixes for these orders, since albite and anorthite, the end members of the acid and basic plagioclases, are set apart as Orders 1 and 2. Lime-soda and soda-lime are so much alike that one must always stop to think which is meant. The prefixes "sodi-" and "calci-" are here suggested. As in the names of normal classes, here also normal rocks drop the prefix; "sodi-," therefore, is seldom necessary. To the rocks of the hinge families, namely, those which contain no plagioclase, "ortho-" is prefixed; the feldspar present is orthoclase, microcline, microperthite, or anorthoclase.

In the classification as it now stands the term granite is applied to all those rocks called granite before the introduction of the term monzonite, that is, rocks with more orthoclase than plagioclase (Family 6). Granodiorite, likewise, is used in its original sense, that is for a rock between granite and diorite (Family 7). If use is made of the monzonitic terms, the limited family of granite, between quartz-monzonite and orthogranite, is called monzogranite (6′), and the limited granodiorite between quartz-monzonite and tonalite, monzotonalite (7′). Likewise the terms syenite (10) and syenodiorite (11), when limited, become monzosyenite (10′), and monzodiorite (11′). Quartz-monzonite or adamellite therefore takes a part of 6 and 7 as 6″–7″, and monzonite 10″–11″ (Figs. 16–19).

[1] For a list of these names with histories of the terms, see the paper above quoted, *Jour. Geol.*, XXVIII (1920), 53 ff. Family names for the monzonite group there given are in general to be omitted. The lists in the succeeding pages are to be followed.

TABLE I

CLASS 1. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{100}{0}$ and $\frac{95}{5}$

Order 1 $Ab_{100}An_0$ to $Ab_{95}An_5$	Order 2 $Ab_{95}An_5$ to $Ab_{80}An_{20}$	Order 3 $Ab_{80}An_{20}$ to Ab_5An_{95}	Order 4 Ab_5An_{95} to Ab_0An_{100}
0 Silexite	(=110)	(=110)	(=110)
1 Orthotarantulite	(=111)	(=111)	(=111)
2 Tarantulite	Granite-greisen		
3	Granodiorite-greisen		
4	Tonalite-greisen		
5 Orthoalaskite	(=115)	(=115)	(=115)
6 Alaskite	Leucogranite		
7 Leuco-albite-granodiorite	Leucogranodiorite	Leucogranogabbro	
8 Leuco-albite-tonalite	Leucotonalite	Quartz-anorthosite	
9 Orthosite	(=119)	(=119)	(=119)
10 Leuco-albite-syenite	Leucosyenite		
11 Leuco-albite-syenodiorite	Leucosyenodiorite	Leucosyenogabbro	Leuco-anorthite-syenogabbro
12 Albitite	Leucodiorite	Anorthosite	Anorthitite
13	(=1113)	(=1113)	(=1113)
14			
15.			
16	Dungannonite		
17	(=1117)	(=1117)	(=1117)
18			
19 Leucolitchfieldite			
20 Leucomariupolite			
21	(=1121)	(=1121)	(=1121)
22			
23			
24	Craigmontite		
25	(=1125)	(=1125)	(=1125)

With the additional families:

6′	Leucomonzogranite		
6″–7″ Leuco-albite-adamellite	Leucoadamellite		
7′	Leucomonzotonalite		
10′	Leucomonzosyenite		
10″–11″ Leuco-albite-monzonite	Leucomonzonite		
11′	Leucomonzodiorite		

TABLE II

CLASS 2. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{95}{5}$ and $\frac{50}{50}$

Order 1 $Ab_{100}An_0$ to $Ab_{95}An_5$	Order 2 $Ab_{95}An_5$ to $Ab_{50}An_{50}$	Order 3 $Ab_{50}An_{50}$ to Ab_5An_{95}	Order 4 Ab_5An_{95} to Ab_0An_{100}
0 Mesosilexite	(=210)	(=210)	(=210)
1 Moyite	(=211)	(=211)	(=211)
2	Quartz-granite		
3	Quartz-granodiorite		
4 Rockallite	Quartz-tonalite		
5 Orthogranite	(=215)	(=215)	(=215)
6 Albite-granite	Granite	Calcigranite	Anorthite-granite
7 Albite-granodiorite	Granodiorite	Granogabbro	Anorthite-granogabbro
8 Albite-tonalite	Tonalite	Quartz-gabbro	Quartz-anorthite-gabbro
9 Orthosyenite	(=219)	(=219)	(=219)
10 Albite-syenite	Syenite	Calcisyenite	Anorthite-syenite
11 Albite-syenodiorite	Syenodiorite	Syenogabbro	Anorthite-syenogabbro
12 Albite-diorite	Diorite	Gabbro, Norite	Anorthite-gabbro
13 Pulaskite	(=2113)	(=2113)	(=2113)
14	Nephelite-bearing syenite		
15	Nephelite-bearing syenodiorite		
16	Nephelite-bearing diorite		
17 Ortho-nephelite-syenite	(=2117)	(=2117)	(=2117)
18 Albite-nephelite-syenite	Nephelite-syenite		
19 Litchfieldite	Nephelite-syenodiorite	Nephelite-syenogabbro	
20 Mariupolite	Nephelite-diorite	Nephelite-gabbro	
21 Naujaite	(=2121)	(=2121)	(=2121)
22 Beloeilite		Heronite	
23			
24 Toryhillite		Lugarite	
25 Urtite, Fergusite, Uncompahgrite	(=2125)	(=2125)	(=2125)
With the additional families:			
6′	Monzogranite		
6″–7″ Albite-adamellite	Adamellite	Calciadamellite	Anorthite-adamellite
7′	Monzotonalite		
10′	Monzosyenite		
10″–11″ Albite-monzonite	Monzonite	Calcimonzonite	Anorthite-monzonite
11′ Albite-monzodiorite	Monzodiorite	Monzogabbro	Anorthite-monzogabbro

TABLE III

CLASS 3. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{50}{50}$ and $\frac{5}{95}$

Order 1 $Ab_{100}An_0$ to $Ab_{65}An_{35}$	Order 2 $Ab_{65}An_{35}$ to $Ab_{50}An_{50}$	Order 3 $Ab_{50}An_{50}$ to Ab_1An_{99}	Order 4 Ab_1An_{99} to Ab_0An_{100}
0	(=310)	(=310)	(=310)
1	(=311)	(=311)	(=311)
2			
3			
4			
5 Melaorthogranite	(=315)	(=315)	(=315)
6 Mela-albite-granite	Melagranite	Melacalcigranite	
7 Mela-albite-granodiorite	Melagranodiorite	Melagranogabbro	
8 Mela-albite-tonalite	Melatonalite	Mela-quartz-gabbro	
9 Melaorthosyenite	(=319)	(=319)	(=319)
10 Mela-albite-syenite	Melasyenite		
11 Mela-albite-syenodiorite	Melasyenodiorite	Melasyenogabbro	Ricolettaite
12 Mela-albite-diorite	Meladiorite	Melagabbro	Yamaskite
13 Orthoshonkinite	(=3113)	(=3113)	(=3113)
14 Shonkinite	Oligoclase-(andesine-) shonkinite	Labradorite-(bytownite-) shonkinite	
15			
16			
17 Nephelite-shonkinite	(=3117)	(=3117)	(=3117)
18			
19 Melalitchfieldite		Mela-nephelite-syenogabbro	
20 Melamariupolite		Theralite	
21	(=3121)	(=3121)	(=3121)
22			
23			
24			
25 Bekinkinite, Missourite, Farrisite	(=3125)	(=3125)	(=3125)

With the additional families:

6′	Melamonzogranite		
6″–7″ Mela-albite-adamellite	Mela-adamellite	Melacalciadamellite	
7′	Melamonzotonalite		
10′	Melamonzosyenite		
10″–11″ Mela-albite-monzonite	Melamonzonite	Melacalcimonzonite	
11′	Melamonzodiorite		

TABLE IV

CLASS 4. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{5}{95}$ and $\frac{0}{100}$

Order 1 "Ores" less than 5 per cent	Order 2 "Ores" between 5 and 50 per cent	Order 3 "Ores" between 50 and 95 per cent	Order 4 "Ores" more than 95 per cent
0 Dunite	Chromite-dunite, Magnetite-dunite	Olivine-chromitite, Olivine-magnetitite	Chromitite, Magnetitite
1 Hornblende-dunite			
2 Pyroxene-bearing-hornblende-dunite			
3 Hornblende-bearing-pyroxene-dunite			
4 Pyroxene-dunite			
5 Mica-peridotite, Amphibole-peridotite, Scyelite, Cortlandite			
6 Olivinite (?)	Valbellite (?)		
7 Wehrlite	Koswite		
8 Lherzolite, Diallage-peridotite, Saxonite	Harzbergite		
9 Amphibolites, Hornblendites, Biotite-pyroxenites			
10	Olivine-bahiaite		
11	Bahiaite, Cromaltite		
12 Diallagite, Bronzitite, Hypersthenite, Websterite		Ilmenite-enstatitite, Magnetite-pyroxenite	

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De irst, de geiht,
Dit is de tweit';
Will wünschen dat de't ok noch deiht.
Un wenn hei't dauhn deiht, kann hei gahn,
Ick heww an em dat Minig dahn.
Wenn Einer dauhn deiht, wat hei deiht,
Denn kann hei nich mihr dauhn, as hei deiht.

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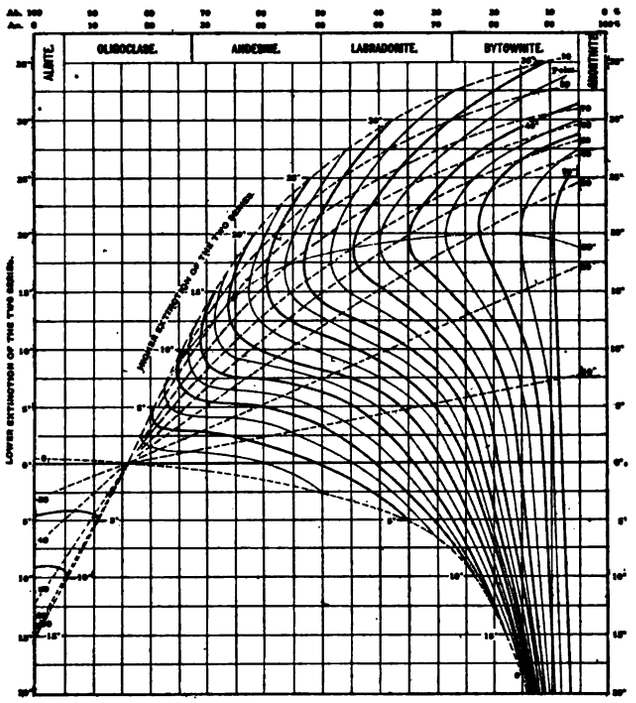

FIG. 23—Extinction angles in sections from the zone at right angles to (010) when the albite twinning is combined with Carlsbad twinning. Solid lines, extinction angles; broken lines, poles. (After Michel-Lévy.)

FIG. 24.—THE PLAGIOCLASE FELDSPARS

A. Curve of specific gravities of the plagioclases.

B. Curve showing the values of 2V and the optical characters. (After Wright.)

C. Curve of indices of refraction. (Modified from Rosenbusch-Wülfing.)

D. Curves of indices of refraction in cleavage flakes parallel to (010) and (001). Broken lines for (001): solid lines for (010) or both (010) and (001). (After Tsuboi.)

E. Extinction angles on (010). (From the diagram given by Wülfing after the values of Max Schuster.)

F. Extinction angles on (001). (Wülfing after Schuster.)

G. Extinction angles from a to the (010) cleavage in sections cut at right angles to both (010) and (001). (Becker and Becke.) The inset cross sections show the (+) and (−) directions of extinction to a.

H. Extinction angles in microlites in the zone (010): (001). (After Wülfing, modified by Johannsen to indicate angles less than 45°.)

I. Extinction angles in sections cut at right angles to b. (Fedorow.)

K. Extinction angles in sections cut at right angles to either bisectrix. Solid line shows angles from the twinning lamellae in sections at right angles to a. Broken line, *L*, angles measured from the (001) cleavage in sections at right angles to c. Dotted line, *M*, angles measured from the trace of (010) in sections at right angles to c. (After the diagram constructed by Wülfing from values given by Fouqué.)

N. Maximum extinction angles in the zone at right angles to (010), measured from the albite twinning lamellae. (Statistical method of Michel-Lévy, modified by Johannsen to indicate angles less than 45°.)

The letters preceding or following the numerical values in the diagram indicate, where there is possibility for confusion, the curves to which these numbers belong.

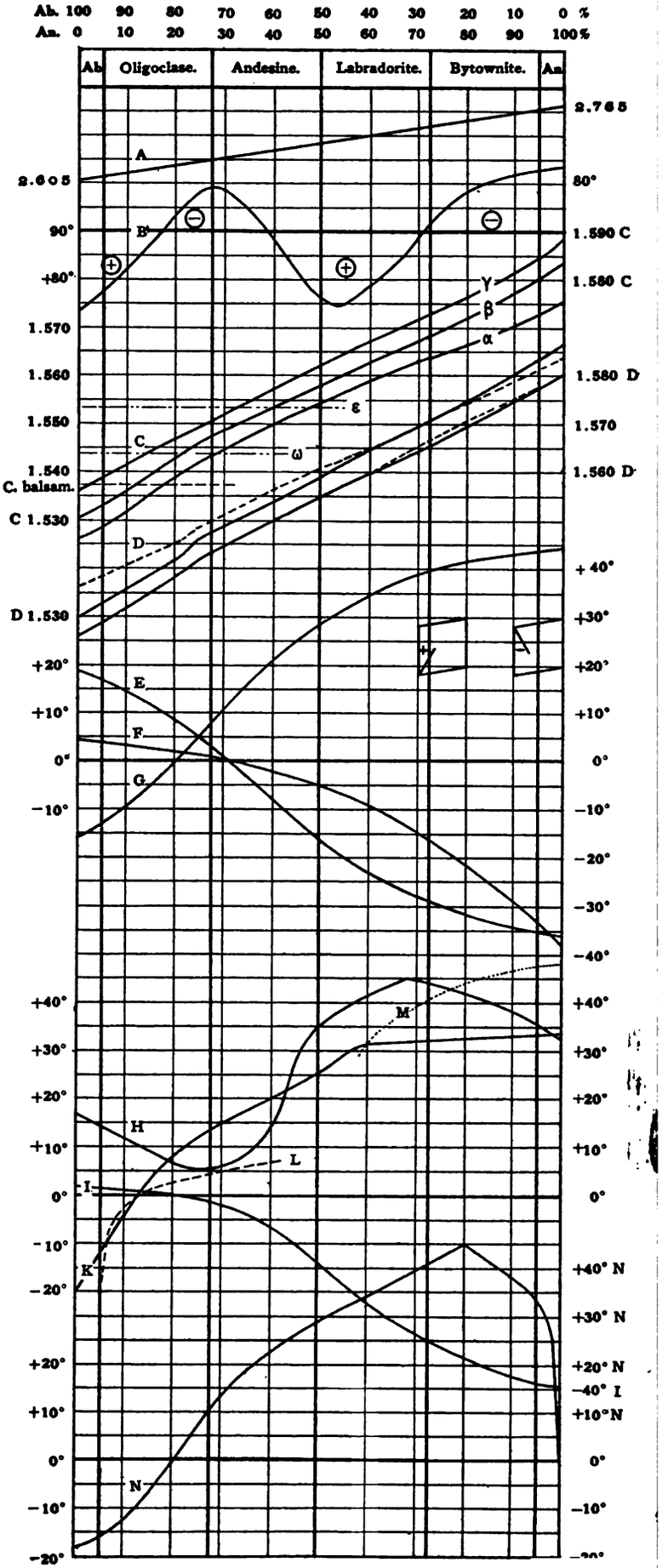

FIG. 24

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